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**USER MANUAL FOR VICONOPT**

**AN EXACT ANALYSIS AND OPTIMUM DESIGN PROGRAM  
COVERING THE BUCKLING AND VIBRATION OF PRISMATIC  
ASSEMBLIES OF FLAT IN-PLANE LOADED, ANISOTROPIC PLATES,  
WITH APPROXIMATIONS FOR DISCRETE SUPPORTS AND  
TRANSVERSE STIFFENERS**

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**UNIVERSITY OF WALES, COLLEGE OF CARDIFF  
AN EXACT ANALYSIS AND OPTIMUM DESIGN PROGRAM  
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## 1 SUMMARY

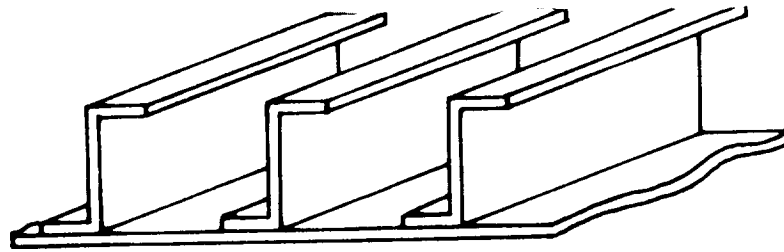
A computer program which is designed for efficient, accurate buckling and vibration analysis and optimum design of composite panels is described. The capabilities of the program are given along with detailed user instructions. It is written in FORTRAN 77 and is operational on VAX, IBM and CDC computers and should be readily adapted to others. Several illustrations of the various aspects of the input are given along with example problems illustrating the use and application of the program.

## 2 INTRODUCTION

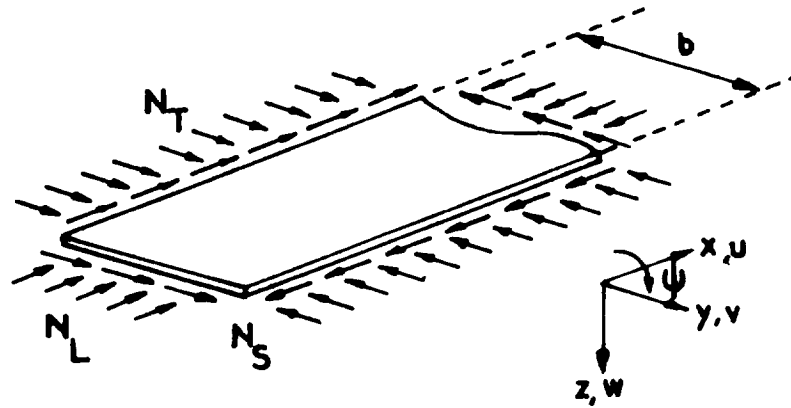
VICONOPT (VIPASA with CONstraints and OPTimization) is a FORTRAN 77 computer program with approximately 23000 lines of coding which incorporates the earlier programs VIPASA (Vibration and Instability of Plate Assemblies including Shear and Anisotropy) and VICON (VIPASA with CONstraints). It covers any prismatic assembly of anisotropic plates each of which can carry any combination of longitudinally invariant in-plane stresses. Figure 2.1 illustrates the stiffened panels and other plate assemblies covered and also shows the forces, per unit length of plate edge, which represent the in-plane stresses, i.e.  $N_L$  for longitudinal compression,  $N_T$  for transverse compression and  $N_S$  for shear. Negative forces are permitted, e.g. to give tension.

VICONOPT may be used as either an analysis or an optimum design program. The analysis features, discussed in chapter 3 of this manual and in reference 1, cover the calculation of eigenvalues, i.e. the critical load factors in buckling problems or the natural frequencies in undamped vibration problems, with the option of finding the corresponding mode shapes and associated perturbation stress levels. The optimum design features, discussed in chapter 4 of this manual and in reference 2, use the buckling analysis results within a sizing strategy to converge on a safe design of low (i.e. near optimum) mass.

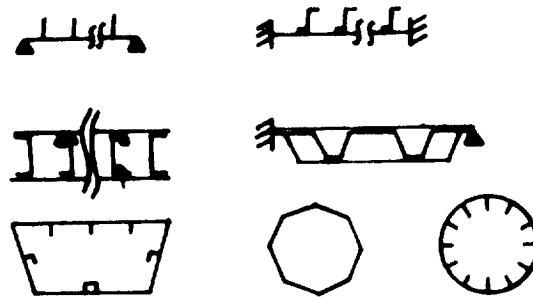
VICON (and hence also VICONOPT) can be used to solve any analysis problem which could otherwise be solved by VIPASA, but includes substantial additional capability as well. VIPASA assumes modes with sinusoidal longitudinal variation of half-wavelength  $\lambda$ , whereas VICON modes are sums of such modes with  $\lambda$  being different for each mode summed. The theory of VIPASA is "exact", in the sense described below, and is retained in VICON in an enhanced form. Results obtained by this route through VICON are frequently referred to below as "VIPASA results" because it is a convenient way of indicating their exactness. The remaining ways in which VICON differs from VIPASA involve approximations and so results which use such features are frequently referred to below as "VICON results", to indicate that approximations have been made. Hence it is convenient below to summarize



(a)



(b)



(c)

Figure 2.1 Indication of the range of prismatic plate assemblies to which VICONOPT applies. (a) Part of a typical prismatic plate assembly. (b) A component plate, showing the basic force system and the plate axis system. (c) Representative cross-sections.

the theory used to obtain VIPASA results separately from that used to obtain VICON results.

VICONOPT extends the capability of VICON by the inclusion of a sizing strategy which combines the well-proven mathematical programming optimizer CONMIN and a method which scales the design to achieve and maintain stability, to produce a final design efficiently with the reasonable assurance that an optimum has been reached.

VICONOPT is the first step towards a program which will ultimately supersede the widely used program PASCO and will have capabilities which either replace, include or are additional to those within PASCO. VICONOPT does not include some PASCO features (e.g. material and stiffness constraints and approximations for panel imperfections), but when these features are absent from a problem the extended analysis capability and improved sizing strategy make VICONOPT much more powerful than PASCO.

VIPASA was developed with Ministry of Defence support under the leadership of the late Professor W.H. Wittrick and the first author at the University of Birmingham in 1974 (refs. 3,4) and was enhanced at NASA-Langley Research Center under the leadership of the second author, prior to release by COSMIC in 1976 (ref. 5). NASA then developed the design program PASCO, which incorporates VIPASA as its principal analysis tool, under the leadership of the second author and W.J. Stroud (refs. 6,7). The main theory of VICON (ref. 8) and a preliminary in-house version of the program were completed by the first two authors and C.J. Wright in 1982 at the University of Wales Institute of Science and Technology (UWIST), being partially funded by NASA-Langley Research Center and by British Aerospace (BAe). The conversion of VICON to a user friendly form, with the introduction of additional theory and a design capability, is represented by this release of VICONOPT (version 1.1) in April 1990, with partial funding again made available by NASA and BAe.

VICONOPT is available to US users from COSMIC\* and details of release to other users are available from the first author. The principal aims of this manual are to describe the program's capabilities and to present the user instructions necessary for its application. Example problems are given to illustrate specific input requirements and timing estimates as a function of problem size are developed. To avoid obscuring the primary aim of the manual, the novel aspects of the theory are not repeated here because they are available in the references cited.

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### 3 ANALYSIS FEATURES OF VICONOPT

#### 3.1 Main Features of the VIPASA-Type Analysis Option of VICONOPT

VIPASA (ref. 3) uses the stiffness matrix method based on exact flat plate theory. It also uses a theoretically derived algorithm which guarantees convergence on all required eigenvalues (refs. 3,9) and which permits the user to employ multi-level substructuring very concisely and flexibly (ref. 10) to reduce solution times, data preparation times and computer memory usage.

The mode of buckling or vibration is assumed to vary sinusoidally in the longitudinal direction  $x$  (with displacement amplitudes  $u$ ,  $v$ ,  $w$  and  $\psi$  relating to the axes  $x$ ,  $y$  and  $z$  as shown in figure 3.1(b)) and with half-wavelength  $\lambda$ , computation being performed for each of a set of user specified values of  $\lambda$ . The sinusoidal assumption implies either appropriate end support conditions or that  $\lambda$  is much smaller than  $\ell$ , the length of the plate assembly. If none of the plates are loaded in shear, i.e.  $N_S = 0$ , and if they are all either isotropic or orthotropic, the nodal lines (i.e. lines of zero displacement) are straight and parallel to the  $y$  axis of figure 2.1 and therefore are consistent with simply supported ends so long as  $\lambda$  divides exactly into  $\ell$ . Otherwise, i.e. if any plates are anisotropic or loaded in shear, the solutions obtained approximate the results for such end conditions and become excessively conservative as  $\lambda$  approaches  $\ell$ . The form of plate anisotropy covered is that for which the coupling stiffness matrix  $[B]$  is null, the out-of-plane bending stiffness matrix  $[D]$  is fully populated and the in-plane membrane stiffness matrix  $[A]$  has  $A_{13} = A_{23} = 0$ , where the symbols are defined in the conventional way. The form of orthotropy covered differs from this anisotropic case by the additional requirement that  $D_{13} = D_{23} = 0$ . Thus in all cases bending and membrane behaviours are uncoupled and orthotropy is assumed for the membrane case with the principal elastic axes parallel to the  $x$  and  $y$  axes of figure 2.1(b). Program execution times are much improved if all plates are isotropic or orthotropic and have  $N_S = 0$ , because then all the stiffness calculations use real arithmetic.

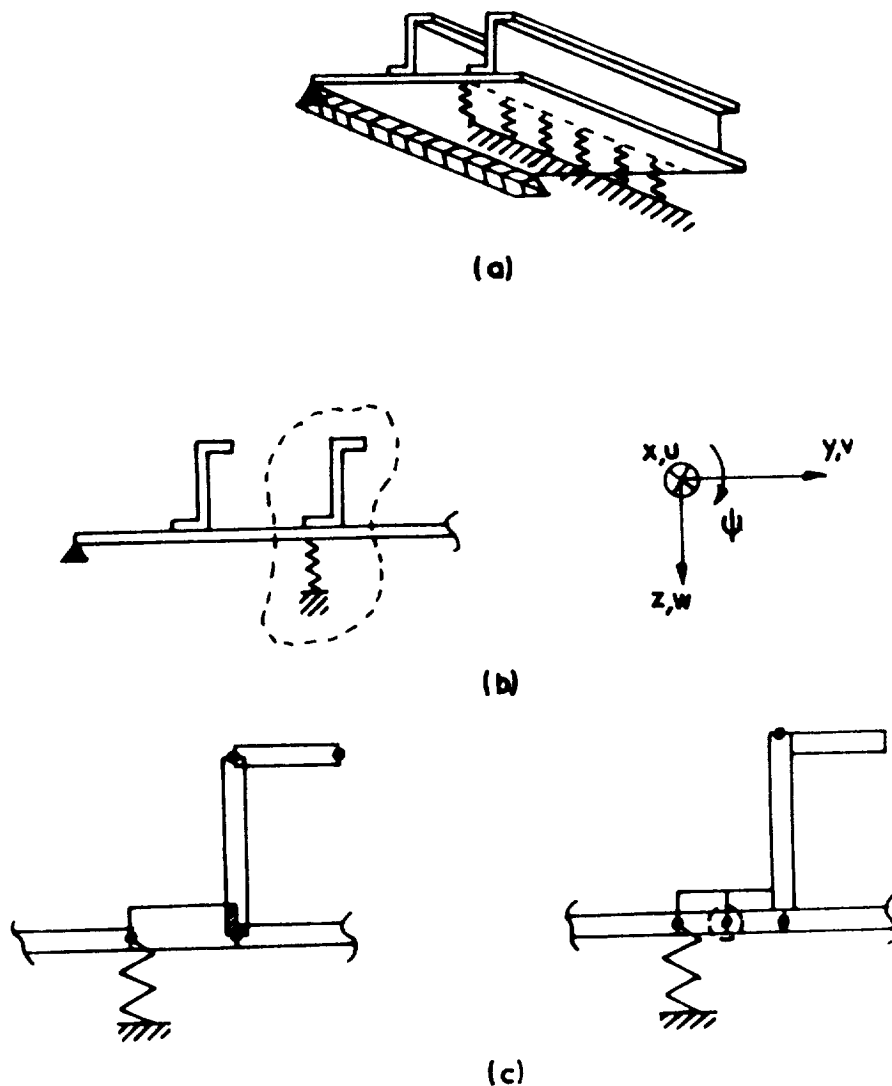


Figure 3.1 Part of a stiffened panel, with the thicknesses exaggerated, showing two longitudinally invariant supports of which one is rigid and the other is elastic. (a) Isometric view. (b) Cross-section, showing axis system and displacements. (c) Alternative models for the ringed part of (b). The solid circles are the nodes, i.e. end views of the line junctions between plates. The left-hand model uses offsets to model the lower flange and the attached skin as a single plate, but accounts for the shaded areas twice. The right-hand model uses offsets more extensively, both to avoid such double counting of areas, and also to connect the lower flange and the web at sufficient positions (see the circled node) to enable both to be anisotropic with  $[B] = [0]$ , even though modelling them as a single plate would give  $[B] \neq [0]$ .

Otherwise the stiffness matrix of the structure is complex (ref. 1), although real arithmetic is still used for any substructures which satisfy this requirement.

Dead load values of  $N_L$ ,  $N_T$  and  $N_S$  are permitted for both buckling and vibration problems. In the former case they are additional to live load values which are factored until buckling occurs. Plates must be connected together rigidly but figure 3.1 illustrates that offset (i.e. eccentric in cross-section) connections between them are permitted and longitudinally invariant rigid or elastic longitudinal line supports can be applied to any combination of the freedoms where they are connected. It is also possible to transform from Cartesian to cylindrical coordinates, or vice-versa, at any desired stages of data assembly in a very concise and flexible way. This permits cylindrical parts of cross-sections to be represented as numerous flats without the user having to calculate the alignment of each flat, and has many other uses.

### 3.2 Main Features of the VICON-Type Analysis Option of VICONOPT

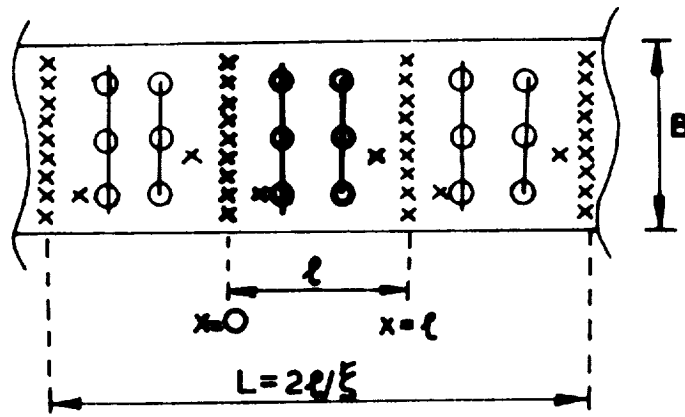
VICON differs from VIPASA in many ways. The key difference is the introduction of Lagrangian multipliers to couple the responses at different values of  $\lambda$ . The advantages of doing this are discussed in the next section and the algorithm which guarantees convergence on all required eigenvalues (ref. 9) had to be extended to include this use of Lagrangian multipliers (ref. 11).

The Lagrangian multiplier analysis assumes (ref. 8) that the deflections of the plate assembly can be expressed as a Fourier series involving an appropriate set of half-wavelengths  $\lambda$ . The total energy of the panel (with inertia effects included in vibration problems) is expressed in terms of the VIPASA stiffness matrices corresponding to these values of  $\lambda$ , together with the conventional stiffness matrices of any supporting structure. Then the required governing equations are obtained by using the method of Lagrangian multipliers to minimize the total energy subject to a set of constraints.

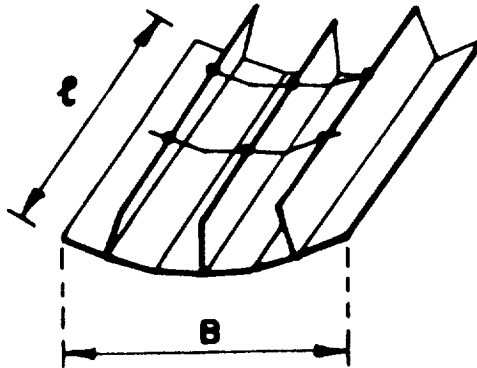
The results given by VICONOPT are for an infinitely long plate assembly with supports, including any supporting structures, which repeat at longitudinal intervals of  $\ell$ , so that the plate assembly and its supports form identical lengthwise bays of length  $\ell$ , see figure 3.2(a). The figure illustrates that each constraint of the set restrains any chosen degree of freedom of one node of the plate assembly at one value of  $x$  in the range  $0 \leq x < \ell$ , so that the restraint is a point restraint which can be used to represent a rigid point support, an elastic point support, or a point attachment to a supporting structure.

Each supporting structure is an assembly of beam-columns lying in the  $yz$  plane with three in-plane freedoms  $v$ ,  $w$  and  $\psi$  (but no out-of-plane freedom  $u$ ). The beams may be aligned by means of rotations, offsets, cylindrical coordinate transformations, or by forming substructures, in exactly the same way as for plates. The nodes which are used in the final connection list of the supporting structure are a subset of the nodes of the panel, and any combination of the three in-plane freedoms can be attached to the panel freedoms at each of these nodes. Note that transverse beam-columns need not be attached directly to the skin of a stiffened panel, e.g. see figure 3.2(b).

The results assume that the mode of buckling or vibration repeats over a length  $L = 2\ell/\epsilon$  for some value  $0 \leq \epsilon \leq 1$ . Each rational value of  $\epsilon$  implies a repetition of the mode over  $M$  lengthwise bays, i.e. over a length  $M\ell$ , for some integers  $M$ ,  $n$  such that  $\epsilon = 2n/M$ , e.g. see figure 3.2(a) on which  $\epsilon = 2/3$ ,  $M = 3$  and  $n = 1$ . It is convenient to express the interval of repetition in terms of  $\epsilon$  rather than of  $M$  and  $n$  because the finite range  $0 \leq \epsilon \leq 1$  covers the entire range of  $M$  from zero to infinity, and also because reference 12 shows that the eigenvalues are functions of  $\epsilon$ , but not of  $M$  and  $n$  separately. The program obtains results over a range of  $\epsilon$  values specified by the user (see section 3.3.2, page 13). For buckling problems, the user must ensure that the appropriate range of  $\epsilon$  is examined that will yield the lowest buckling load. It is only necessary to supply data specifying point supports and beams lying in the interval  $0 \leq x < \ell$ . Thus for the plate assembly and supporting structure of figure 3.2(a), data is given for the portion



(a)



(b)

Figure 3.2 Illustration of the infinitely long structure to which the Lagrangian multiplier method of VICONOPT relates. (a) Plan view of a plate assembly for which  $\epsilon = 2/3$ , with crosses denoting point supports and circles denoting points of attachment to transverse supporting structures consisting of beam-columns. (b) Isometric view of a length  $\ell$  if the plate assembly of (a) is a polygonal blade-stiffened panel, with circles denoting points of attachment to the two supporting structures shown.

shown bold, with the program automatically assuming the repetition over successive lengthwise bays which is indicated by the faint lines.

The program can be used to represent a panel with finite length  $\ell$  and simply supported ends, by representing the simple supports by a line of rigid point supports at  $x = 0$  which each restrain only the appropriate displacement, e.g. displacement in the  $z$  direction for the line of point supports shown on figure 3.2(a). Results obtained in this way have been found (ref. 8) to be reasonably accurate, even though the continuity of the infinitely long plate assembly of the analysis fails to represent the zero moment along the transverse edges at the ends of the finite length panel.

For each analysis, VICONOPT generates an infinite series of appropriate values of  $\lambda$  to use (see table 1 of ref. 8), although in practice the user truncates this to a finite series, to reduce solution time at the expense of some loss of accuracy. The default value for number of  $\lambda$ 's is generally suitable for overall buckling modes of panels supported at intervals of  $\ell$ . The user may select a different number of  $\lambda$ 's which might be required for other types of support and it is recommended that the value be changed for each type of problem investigated to check convergence.

Clearly a principal use of the Lagrangian multiplier route in VICONOPT is to simulate a transverse line support as a line of point supports at  $x = 0$ , as in figure 3.2(a), so as to overcome the difficulty discussed in section 3.1 (see page 6), namely that VIPASA results for large values of  $\lambda$  (e.g.  $\ell/3 \leq \lambda \leq \ell$ ) may be unduly conservative when plates are loaded in shear or are anisotropic. In such cases the user can also check for short wavelength buckling, by performing a VIPASA analysis for such wavelengths, on the same run as is used for the Lagrangian multiplier analysis just described.

### 3.3 Selection of Wavelength Parameters

The most important guide in using and applying VIPASA- and VICON-type analyses will be experience gained in analyzing buckling and vibration problems for plate structures that the user has solved independently by alternative approaches, such as differential equation solutions, handbook formulae and finite element analyses. The user first must model the structure to be analyzed as a prismatic plate assembly having longitudinally invariant in-plane loading. The applicability of the results will depend on the choice of the various wavelengths for which calculations are made which is the responsibility of the user. The following sections discuss some of the aspects which affect this choice.

#### 3.3.1 Selection of Lambda Values for VIPASA-Type Analyses

In the VIPASA-type analysis the plate assembly response is a single sinusoidal mode in the longitudinal direction with half-wavelength  $\lambda$ . If shear and anisotropy are absent, simply supported boundary conditions are satisfied. The exact solution to the problem is obtained by taking  $\lambda = \ell, \ell/2, \ell/3, \dots$ . If all values of  $\lambda$  are examined in the series until the smallest is sufficiently smaller than the smallest plate width, the user will certainly have found the minimum buckling load. Here the smallest plate width means unsupported width between connections to other plates having different alignments. If shear and/or anisotropy are present, results for values of  $\lambda$  much less than  $\ell$  ( $\lambda \leq \ell/4$ ) should remain reasonably accurate and conservative for an infinitely long panel supported at longitudinal intervals of  $\ell$ . The results for larger  $\lambda$ 's are likely to be much more conservative than the user is willing to accept, especially for the case of shear loadings. It is recommended in these cases that a VICON analysis be made so that the support at a boundary can be more accurately modelled.

### 3.3.2 Selection of Response Modes for VICON-Type Analyses

In the VICON-type analysis the plate assembly response is the sum of a series of sinusoidal modes which are constrained to give the desired support conditions. As discussed in section 3.2 (see page 9), the plate assembly analyzed is infinitely long with constraints which repeat at intervals of  $\ell$  and the response mode is one which is repetitive over a length  $L = 2\ell/\epsilon$ . The half-wavelengths used by the program are (from equation 4.5, ref. 12, in which  $m$  and  $q$  have different meanings)

$$\lambda_m = \frac{\ell}{(\epsilon + 2m)} \quad (m = 0, \pm 1, \pm 2, \dots, \pm q) . \quad (3.1)$$

To determine the minimum buckling load with respect to  $\epsilon$ ,  $\epsilon$  is varied from 1 to 0 in a number of equal user controlled steps and the minimum may be selected. This process can be accelerated by the use of a 'FAST' option, which omits calculation of the buckling load for a particular value of  $\epsilon$  if a preliminary check shows that it exceeds that for any value of  $\epsilon$  already considered. The 'FAST' option can be used in an analagous way in a VIPASA-type analysis (see page 12) when finding the minimum buckling load over a range of values of  $\lambda$ .

When  $\epsilon = 0$  and  $m = 0$ , the half-wavelength  $\lambda_m$  becomes infinite. Note that VICONOPT performs exact plate stiffness calculations for this case using a modified form of the beam stiffness calculations, whereas earlier versions of VICON used approximations based on a large finite value of  $\lambda_m$ .

Note that when shear and anisotropy are absent, the overall buckling mode will repeat over a wavelength  $2L$  (i.e.  $M = 2$  and hence  $n = 1$ ), which corresponds to the case  $\epsilon = 1$ . When shear and anisotropic effects are small, one should expect a minimum overall buckling load in the vicinity of  $\epsilon = 1$  and this region should be examined with enough points to ensure that the minimum is obtained within reasonable accuracy. It is recommended that the number of  $\lambda$ 's used in the solution be varied by changing  $q$  (see equation 3.1) to assess the convergence of the solution. The default setting  $q = 5$  usually gives sufficient accuracy, although plate assemblies having constraints at several  $x$  locations in the interval  $\ell$

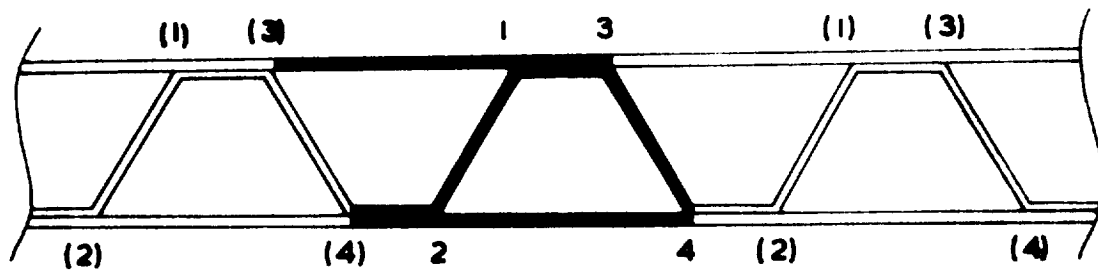
are likely to require more  $\lambda$ 's (i.e. a higher value of  $q$ ) for convergence. Another aspect of convergence is the number of point supports used to simulate a continuous line support. Note that as the number of  $\lambda$ 's is increased, the eigenvalue decreases and as the number of supports increases, the eigenvalue increases.

It is not recommended that the VICON-type analysis be routinely used for modes which are dominated by many half waves in the length (i.e.  $\lambda \ll \ell$ ) although such a calculation is possible, because the number of  $\lambda$ 's required for accurate results would be quite large, and the result would differ little from a much quicker VIPASA-type analysis at the appropriate  $\lambda$ . An efficient, and reasonably accurate, method of working is to perform VICON analysis with a small number of  $\lambda$ 's to obtain overall modes (e.g. by setting  $q = 2$  so that values of  $\lambda$  smaller than  $\ell/5$  are excluded in equation 3.1), and to perform VIPASA analysis in the same run to obtain local modes using these smaller values of  $\lambda$ . This approach is particularly useful in design problems (e.g. see example 6.4, page 133) because analysis must be performed at each step of the design process. If necessary, the final design should be re-analyzed using a higher value of  $q$  to guard against any instability caused by insufficient accuracy in the calculation of the critical eigenvalues.

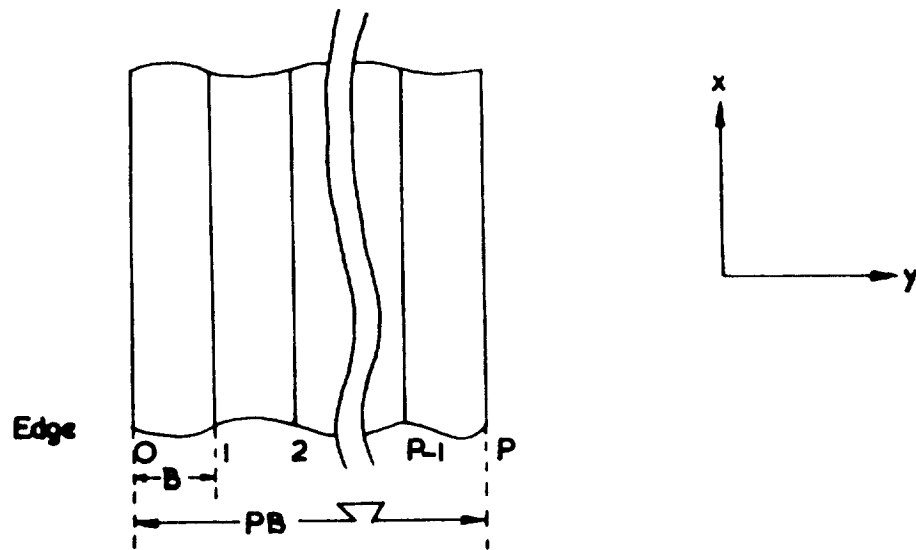
### 3.4 Repetitive Cross-sections

Many plate assemblies have cross-sections which are repetitive. They can be analyzed by assuming infinite width and using recurrence equations to enable computation (and data preparation) to involve only a datum repeating portion, e.g. see figure 3.3(a). The physical assumptions on which this analysis are based can be described by reference to figure 3.3(b) as follows.

Although the theory (see ref. 12) assumes infinite width, any real plate assembly to which it is applied will have a finite number,  $P$ , of repeating portions which are each of width  $B$ , so that the total width is  $PB$  and the portions are connected along the  $P + 1$  edges shown. Here the term edge is taken to include all nodes common to the connected portions, e.g.



(a)



(b)

Figure 3.3 Plate assemblies that consist of repeating portions. (a) A typical repetitive cross-section, with the datum repeating portion shown bold. The numbers are node numbers, with the brackets indicating that all repeating portions have an implied node numbering identical to that of the datum portion. (b) Plan view of a repetitive plate assembly with  $P$  repetitions.

nodes 3 and 4 on figure 3.3(a). Now suppose that the infinitely wide results are intended to represent the panel as simply supported along edges 0 and P. A necessary, but not necessarily sufficient, condition for this to be achieved is that the mode should repeat at transverse intervals of  $2PB$ . This is the only condition imposed by the program. It gives exact results in VIPASA analyses when shear and anisotropy are absent, and also in certain VICON analyses which produce straight nodal lines (i.e. lines of zero displacement) parallel to the x axis.

The longitudinal wavelengths must still be chosen in the ways discussed in section 3.3 (see pages 12-14). In addition the user must select a range of half-wavelengths  $\lambda_T$  in the transverse y direction. This choice is independent of whether a VIPASA or a VICON analysis is being performed. Factors affecting the choice of  $\lambda_T$  are very similar to those affecting the choice of  $\lambda$  in VIPASA. The main difference is that due to the discrete nature of the plate assembly in the y direction compared to its continuity in the x direction, only a finite set of values of  $\lambda_T$  need be considered.

Reference 12 shows that any deflection on edge p ( $p = 0, 1, 2, \dots, P$ ) can be obtained from the corresponding deflection on edge 1 by multiplying by

$$\exp (ip\pi g/P)$$

where g is an integer, so that  $\lambda_T = PB/g$  and g is the number of half wavelengths  $\lambda_T$  across the width PB of the plate assembly. The finite number of values of g which must be considered are all the integers given by  $0 \leq g \leq P$ . (Reference 12 shows, for reasons to do with the complex arithmetic formulation used, that when  $M > 2$  (i.e. when  $0 < \epsilon < 1$ ), computations must usually be performed both for these values of g and for their negatives, i.e. -g. However the program automatically considers these negative values when appropriate and so negative values of g need never be given in data.)

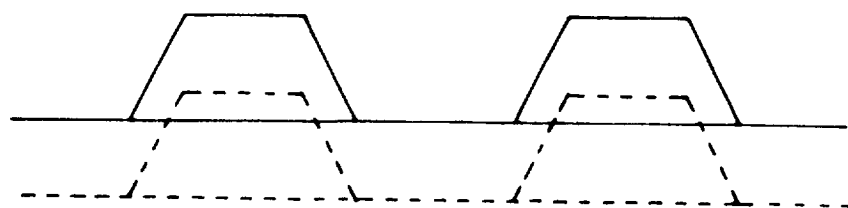
If the above range of g is desired the program will generate it automatically and the only data required is P. If lesser ranges are desired, additional input can be used to specify the desired g values.

When  $P$  is very large, the above range may be excessive and one can save computation by assuming a continuous variation of the eigenvalue with  $\lambda_T$ . If  $\eta = g/P$ , then  $\lambda_T = B/\eta$  and the range  $0 \leq g \leq P$  is replaced by  $0 \leq \eta \leq 1$ . Thus, for an infinitely wide panel, the entire range of  $g$  required as data is covered by varying  $\eta$  from 0 to 1 in a suitable number of steps. This option is available to the user or, as an alternative, additional data enables smaller segments of the range to be examined.

If this feature is used with cylindrical coordinate transformations (see section 5.4, page 59 and Appendix A2.2, page 153) to model a closed rotationally periodic section with  $N$  repeating portions (e.g. an  $N$ -sided polygon),  $P$  should be set to half the number of repeating portions (i.e.  $N/2$ ) because the theory is consistent with the complete mode shape repeating at intervals of  $2PB$ . Note if  $N$  is odd,  $P$  will have a decimal part of .5 .

If shear is present, some error (which experience shows is conservative) would occur for transverse half-wavelengths approaching  $PB$ . However many plate assemblies have much greater bending stiffness in the  $x$  direction than in the  $y$  direction and in such cases the error has usually been found to be small. (This contrasts with the large error given by VIPASA for values of  $\lambda$  approaching  $\epsilon$  when the shear loads  $N_g$  are large. Of course if  $\lambda_T$  is much less than  $PB$ , results are reasonably accurate as well as conservative for simply supported edges.)

When finding the minimum buckling load, a two dimensional search is thus required, with respect to  $\lambda$  and  $g$  (or  $\eta$ ) for a VIPASA-type analysis and with respect to  $\epsilon$  and  $g$  (or  $\eta$ ) for a VICON-type analysis. This can often be accomplished at less computational cost than that for analyzing the full width panel by using the 'FAST' option described earlier in section 3.3.2 (see page 12) to omit calculation of the buckling load for a particular combination of  $\lambda$  or  $\epsilon$  and  $g$  (or  $\eta$ ) if it exceeds that for any combination that has already been considered. The repetitive method is especially useful in a VICON analysis where constraints are applied at a large number of points, as in example 6.3 (see page 120).



(a)



(b)

Figure 3.4 Overall and local modes for  $g = 0$ .  
 (a) Overall mode. (b) Local mode.

The program calculates all modes for  $g = 0$ , but some of them are overall modes, which involve equal displacements  $w$  at every edge on figure 3.3, whereas others involve local buckling for which these  $w$  displacements are negligible, contrast figures 3.4(a) and 3.4(b). The user may choose to discard any buckling load for which the mode is overall because it is incompatible with simple supports on edges 0 and P. Figure 3.4 also illustrates the distinction between half-wavelengths as applied to edge deflections and the actual mode of the structure. Both cases are for  $g = 0$ , i.e. for an infinite half-wavelength  $\lambda_T$ , which only requires that displacements at edges 0, 1, ..., P be the same. In the case of (a) the deflections of all points are essentially identical and so the actual mode appears to have an infinite wavelength. In contrast, the actual mode of (b) clearly has two transverse half waves in the skin of each repeating portion. Therefore, in general one cannot expect the actual mode given by a particular value of  $\lambda_T$  to appear to have half waves of length  $\lambda_T$ .

### 3.5 Timing estimates

VICONOPT prints estimates of the time required per iteration of the analysis, i.e. for each trial value of the eigenvalue. These estimates depend on 5 machine dependent parameters, 12 problem dependent coefficients and the type of analysis required. A justification of the estimates is given in reference 1.

For a particular computer, suitable test problems such as those in sections 6.6 and 6.7 (see pages 140-147) should be run to establish the values of the following 5 parameters:

- $\alpha_R$  = time per update operation in real Gauss elimination (i.e. a real multiplication followed by a real subtraction).
- $\alpha_C$  = time per update operation in complex Gauss elimination (i.e. a complex multiplication followed by a complex subtraction).
- $\beta_R$  = time to calculate stiffnesses for a 'real' plate.
- $\beta_C$  = time to calculate stiffnesses for a 'complex' plate.
- $\beta_B$  = time to calculate stiffnesses for a beam.

The values should be placed in the appropriate initialization statement in the source code at the start of the VICONOPT main program.

For a particular problem, the program calculates the following 12 coefficients:

$t_1$  = number of 'real' plates.

$t_2$  = number of 'complex' plates.

$$t_3 = \sum_s 32 B_s^2 (N_s - \frac{2}{3} B_s)$$

where the summation is over all 'real' substructures,  
 $N_s$  = number of nodes in substructure,  
 $B_s$  = 3 (doubly-connected) or 2 (singly-connected).

$t_4$  = as  $t_3$  but for 'complex' substructures.

$$t_5 = 32B^2 (N - \frac{2}{3}B) + 8(N-B)BR + \frac{2}{3}NR^2$$

where  $N$  = number of nodes in final structure,  
 $B$  = 1 + maximum difference between connected nodes,  
 $R$  = number of constraints in final structure.

$t_6$  =  $t_5$  defined with  $R = 0$  (real VIPASA analysis only, otherwise  $t_6 = 0$ ).

$t_7$  =  $t_5$  defined with  $R = 0$  (complex VIPASA analysis only, otherwise  $t_7 = 0$ ).

$t_8$  = number of beams.

$$t_9 = \sum_s 13\frac{1}{2} B_s^2 (N_s - \frac{2}{3} B_s)$$

where the summation is over all beam substructures,  
 $N_s$  and  $B_s$  defined as for  $t_3$ .

$$t_{10} = \sum_b \{ 13\frac{1}{2} B_b^2 (N_b - \frac{2}{3} B_b) + 4\frac{1}{2} (N_b - B_b) B_b R_b + \frac{1}{2} N_b R_b^2 \}$$

where the summation is over all supporting structures,  
 $B_b$  = 1 + maximum difference between connected nodes,  
 $R_b$  = number of constraints in supporting structure  
(for non-repetitive analysis only, otherwise  $t_{10} = 0$ ).

$t_{11}$  = as  $t_{10}$  but for repetitive analysis only (otherwise  $t_{11} = 0$ ).

$$t_{12} = \frac{1}{6}R^3$$

where  $R$  = number of constraints in final structure.

For a VIPASA analysis, the estimated time per iteration is given by

$$\beta_R t_1 + \beta_C t_2 + \alpha_R(t_3+t_6) + \alpha_C(t_4+t_7).$$

For a non-repetitive VICON analysis (i.e.  $\eta = 0$  or  $1$ ) with  $\epsilon = 0$  or  $1$ , the estimated time per iteration is given by

$$q \{ \beta_R t_1 + \beta_C t_2 + \alpha_R t_3 + \alpha_C(t_4+t_5) \} + \beta_B t_8 + \alpha_R(t_9+t_{10}) + \alpha_R t_{12}.$$

For any other VICON analysis, the estimated time per iteration is given by

$$q' \{ \beta_R t_1 + \beta_C t_2 + \alpha_R t_3 + \alpha_C(t_4+t_5) \} + \beta_B t_8 + \alpha_R(t_9+t_{10}) + \alpha_C t_{11} + \alpha_C t_{12}.$$

Here,  $q$  is the parameter specified in the VICON data line (see page 32 and equation 3.1 on page 13), and  $q'$  is  $(2q - 1)$  for a repetitive analysis with  $\epsilon = 0$ ,  $(2q)$  for a repetitive analysis with  $\epsilon = 1$ , and  $(2q + 1)$  for any analysis with  $0 < \epsilon < 1$ .

## 4 DESIGN FEATURES OF VICONOPT

### 4.1 Design Variables and Dependent Variables

For a design problem VICONOPT uses buckling analysis results to find a stable, low-mass design. The user may select any set of plate breadths, layer thicknesses and layer ply angles as design variables which the program adjusts independently. The remaining plate breadths, layer thicknesses and layer ply angles, together with any plate or substructure rotations and offsets are either held fixed or linked to the values of the design variables to become dependent variables.

### 4.2 Equality Linking, Inequality Linking and Bounds on Design Variables

The user may wish to specify configurational constraints which control changes in the design, for example to maintain geometric consistency and satisfy other logical requirements or to keep parameters within sensible limits in order to maintain practical proportions.

Equality linking is used in design (or in analysis when sensitivities are required) to define the values of dependent variables in terms of the design variables. VICONOPT permits the use of linear equations having the following general format.

$$\sum_{k=1}^{n_D} B_{Dik} X_{Dk} = \sum_{j=1}^{n_I} B_{Iij} X_{Ij} + \sum_{l=1}^{n_F} B_{Fil} X_{Fl} + C_i \quad (\text{for } i=1, \dots, n_D) \quad (4.1)$$

where

- $n_D$  = total number of dependent variables;
- $n_I$  = total number of design (i.e. independent) variables;
- $n_F$  = total number of fixed parameters (i.e. total number of plate breadths, layer thicknesses, layer ply angles and plate/substructure offsets whose value is held fixed);

$[B_D]$  = matrix of dependent variable coefficients;  
 $[X_D]$  = vector of dependent variables;  
 $[B_I]$  = matrix of design variable coefficients;  
 $[X_I]$  = vector of design variables;  
 $[B_F]$  = matrix of fixed parameter coefficients;  
 $[X_F]$  = vector of fixed parameters;  
 $[C]$  = vector of constant values.

Note that the above equations describe the equality linking of all dependent variables except for the angles associated with plate/substructure rotations and cylindrical coordinate transformations which are affected by design variable changes. These are dealt with in the way described under the heading ANGLE definition in section 5.9 (see page 85).

Inequality linking and bounds on design variables are used in design to provide constraints on the values of dependent variables and design variables. Bounds define simple upper and lower limits on a single design variable, whereas inequality linking imposes linear constraints involving a number of dependent variables or design variables, as follows.

$$\sum_{j=1}^{n_V} B_{Lij} X_j \leq \sum_{j=1}^{n_V} B_{Rij} X_j + C_i \quad (\text{for } i=1, \dots, n_C) \quad (4.2)$$

where

$n_V$  = total number of design variables, dependent variables and fixed parameters;  
 $n_C$  = total number of inequalities;  
 $[B_L]$  = matrix of left hand side coefficients;  
 $[B_R]$  = matrix of right hand side coefficients;  
 $[X]$  = vector of design variables, dependent variables and fixed parameters;  
 $[C]$  = vector of constant values.

### 4.3 Buckling Constraints and Sensitivities

The analysis capability of VICONOPT is used to find the eigenvalues (i.e. the critical load factors which cause buckling) for the panel at various stages during the design process. The constraint and sensitivity analysis step of figure 4.1 calculates the buckling constraints from the eigenvalues which are critical, or near to critical, for the configuration at the start point of each sizing cycle. At this start point each design variable is perturbed in turn, the values of the dependent variables being adjusted using equation 4.1. The changes in eigenvalues caused by this perturbation divided by the size of the perturbation constitute the buckling sensitivities. A quick and reliable approximate method (described in ref. 2) is used for finding the perturbed eigenvalues and automatic recovery procedures are included to find them with certainty when the data is unsuitable for approximation.

### 4.4 Sizing Strategy

The VICONOPT sizing strategy shown in figure 4.1 contains three types of resizing step: the initial stabilization step, the CONMIN optimization step and the stabilization step. The initial stabilization step brings unstable or over-stable initial designs to a 'just' stable configuration by altering design variable thicknesses to converge on a configuration such that the most critical eigenvalue for the set of buckling modes specified by the user becomes unity. The CONMIN optimization step uses linear programming techniques (ref. 13) to alter design variables so that the plate assembly mass is reduced without violating the buckling and configurational constraints. The stabilization step follows the CONMIN optimization step and returns the optimized configuration to a 'just' stable condition. This step is necessary because the linear assumptions made during optimization are likely to require correction.

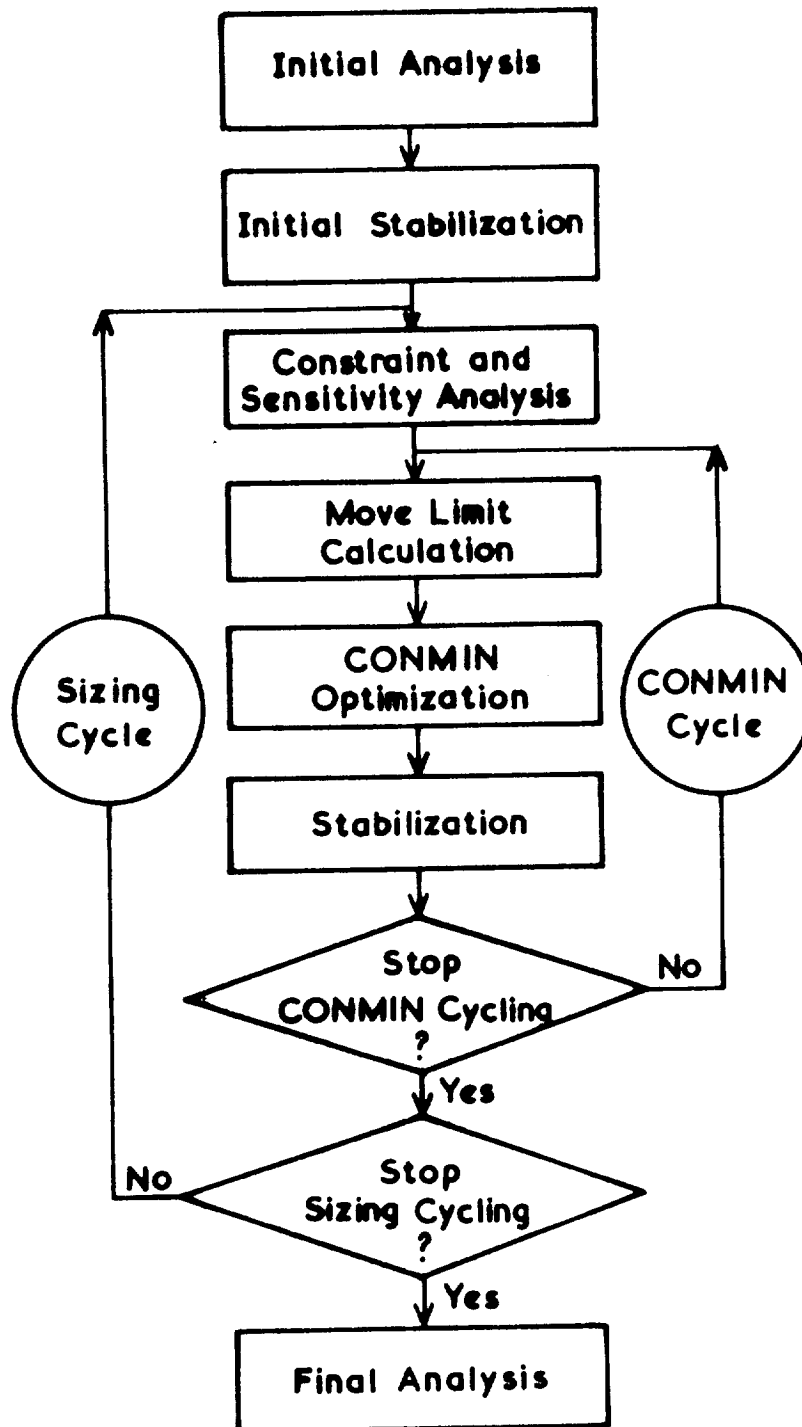


Figure 4.1 VICONOPT sizing strategy.

Stabilization makes design convergence quicker and more likely to obtain a design which is both feasible and optimum. The use of stabilization is, however, optional and if users do not select this option (or if its use violates bounds on thicknesses), the sizing strategy of figure 4.1 operates without either of the stabilization steps and without CONMIN cycling, so that each sizing cycle contains only one move limit calculation step and one CONMIN optimization step.

The sequence of move limit calculation, CONMIN optimization and stabilization steps make up one of the CONMIN cycles of figure 4.1. This sequence re-uses the information calculated by the time consuming constraint and sensitivity analysis step to tailor the linear optimization of CONMIN by adjusting CONMIN move limits for subsequent CONMIN cycles. The result of this sequential tailoring (described more fully in ref. 2) is that the change in mass required to stabilize the design is generally much lower than the saving in mass achieved by CONMIN. The mass of the stabilized design at the end of each sizing cycle when CONMIN cycling has stopped will thus approach the lowest possible for the sizing cycle. CONMIN cycling will stop if: (1) the move limits calculated in the move limit calculation step are either excessively large, excessively small or not significantly different from previous move limits, if (2) the relative mass difference between two successive optimized configurations is within a default or user specified limiting value, or if (3) the number of CONMIN cycles has exceeded a maximum number which can be specified by the user.

When CONMIN cycling has stopped the sizing cycle of figure 4.1 is re-entered and the constraint and sensitivity analysis step is applied to the design which had the lowest stable mass in the previous sizing cycle. The process is repeated until sizing cycling stops, i.e. until the user specified maximum number of sizing cycles is reached, or until convergence based on the relative mass difference of subsequent sizing cycles is within a default or user specified limiting value, a user specified minimum number of sizing cycles having been exceeded.

#### 4.5 Selection of Wavelength Parameters

As in analysis problems, the selection of wavelength parameters defining each buckling mode to be considered by the program is at the discretion of the user, and will affect the applicability of results. In the design process however, the problem is further complicated by the changing panel configuration and the user should select a range of buckling modes, any one of which may become critical as sizing progresses. The program will recognize any of these buckling modes which are far from critical and will avoid calculating their buckling constraints and sensitivities. These modes are not considered during the CONMIN optimization step of each CONMIN cycle although the stabilization step is based on all the modes supplied by the user.

## 5 INPUT DATA PREPARATION

The input is free field with the following general features:

- (1) Numeric data may be separated by blanks or commas.
- (2) Trailing zeros on lines of data having a specified number of entries need not be entered.
- (3) Alphabetic characters may be in either upper or lower case.
- (4) Comments may be inserted on any line after inserting a \$. Data may be resumed on the same line after a second \$.
- (5) A capability for generating data which repeats in a regular pattern, such as coordinates or connections, is available and described in section 5.12 (see page 103).
- (6) If it is desired to enter more data than will fit on one line, it may be continued on the next line by typing a % at the end of the first line. This process may be repeated as many times as are necessary.
- (7) Different versions of a problem for which only a few data changes are required may be analyzed consecutively, or considered together in the design process, by making use of the CHAnge set facility described in section 5.13 (see page 104).

The input data is separated into several groups which are each identified by a descriptive heading that precedes the numeric data. These groups may appear in any order. With the exception of the RESet group (see page 95), each group must appear only once (unless the CHAnge set facility is being used, see page 104). All data in a group must appear without interruption under that group heading. Only the first three letters of each heading (unless otherwise indicated) are used by the program so that the remaining characters are only used as a prompt to the user. The necessary letters for each name are identified with capital

letters in this manual. In some of the groups, the numeric data is preceded by or interspersed with alphabetic data identifying alternative forms or the use of optional features: such requirements will be presented in the detailed descriptions of individual data groups later in chapter 5. Each data group which consists of a descriptive heading followed by one or more lines of data is identified in the following sections with a large arrow (formed from asterisks) to the left of the heading line; each such group that is always required in any run is identified by using a double arrowhead. Certain data groups are present in almost all runs; these are also indicated with the double arrowhead but the exceptional case when they are not required is stated and underlined in the text just below the heading. Some data groups have several different forms of input depending on the requirements of the problem. These alternative forms are identified in the left margin by the symbol †. In addition to the data groups, there is input consisting of a single line containing one item of text which may be followed by one or more items of numeric data. These lines can also appear in any location. Specific examples of most of the data input are given in the example problems of chapter 6.

For a given problem, the data in many of the groups is not applicable and such groups may be omitted. Because of default values contained in the program certain other groups may also not be required. The minimum number required are the PLate data, WALL data, MATerial data (unless the in-plane and bending stiffness matrices [A] and [D] have been input directly for all plates), and either the CONnection or ATTachment data. Though there are exceptional cases where they are not required, the ALIgnment data and the CONnection data will appear in almost every problem.

Sections 5.1 - 5.13 (see pages 32-105) describe all the program input in a logical sequence. New users are advised to study sections 5.1 - 5.5 and the LONGitudinal line supports portion of section 5.6 (i.e. pages 32-65) first, since they contain sufficient information for the preparation of data for many simple problems. The remainder of section 5.6 and sections 5.7 - 5.13 (i.e. pages 66-105) introduce additional capabilities which should be studied separately as required.

Figure 5.1 is an alphabetic index to the data groups and RESet variables described in sections 5.1 - 5.13. The user may wish to photocopy this for use as an aide-memoire when preparing data. A more comprehensive index will be found at the end of this manual.

The program prints an echo of the input data, followed by an organized listing which shows all the data groups with descriptive headings, in the order in which they appear in chapter 5 of this manual. This listing includes default values for any necessary quantities which were omitted from the input data, and the user is advised to study it carefully, checking that the instructions in this manual have been followed correctly, that numeric values have been entered correctly and in the right order, and that the default values supplied by the program are appropriate.

After the organized listing, the program prints any (fatal) error messages and (non-fatal) warning messages generated by the input data. The former category includes the absence of any of the required data groups listed above, as well as various cases of inconsistent or incomplete data, and causes termination of the program.

Item	Page	Item	Page
ACCuracy . . . . .	35	MATerial . . . . .	42
ALIgnment . . . . .	53	MODal density . . . . .	36
ANALysis . . . . .	33	MODEs . . . . .	36
ANGLE definition . . . . .	85	NC . . . . .	99
ATTachment . . . . .	63	NEMAX . . . . .	99
AXIal loading . . . . .	52	NIMAX . . . . .	99
BALignment . . . . .	70	NLEN . . . . .	99
BEAMs . . . . .	69	NODEs . . . . .	93
BOUNds . . . . .	87	NOEcho . . . . .	41
BUCKling . . . . .	33	NOSTabilize . . . . .	34
CHAnge set . . . . .	41	NUMX . . . . .	99
CMASS . . . . .	96	NUMY . . . . .	99
CSTAB . . . . .	96	NWID . . . . .	100
CONNECTION . . . . .	62	PFAst . . . . .	40
CROSS-sectional plotting . . . . .	92	PLAte . . . . .	49
DESIgn . . . . .	34	PLot . . . . .	91
ECHO on/OFF . . . . .	41	POInt supports . . . . .	66
EIGenvalues . . . . .	35	PSMOVE . . . . .	100
END . . . . .	41	REPetitive plates/beams . . . . .	77
EXPlanation . . . . .	41	RESet . . . . .	95
FACBND . . . . .	96	SENSitivities . . . . .	81
FASt . . . . .	39	SF . . . . .	100
FOUndations . . . . .	67	SMASPR . . . . .	100
GEOMetry . . . . .	40	SMOVE . . . . .	100
HORIZ . . . . .	97	STabilize on/OFF . . . . .	34
HT . . . . .	97	STress resultant . . . . .	50
IDBUG . . . . .	97	SUPporting structures . . . . .	74
IDEFF . . . . .	97	TITle . . . . .	32
INMOD . . . . .	97	TOLA . . . . .	101
INTM . . . . .	97	TOLB . . . . .	101
INTP . . . . .	97	TOLG . . . . .	102
IPLSY . . . . .	98	TOLM . . . . .	102
ISPC . . . . .	98	TRAnsverse wavelength . . . . .	79
ISYM1 . . . . .	98	TRIAL values . . . . .	35
ISYM2 . . . . .	98	VERT . . . . .	97
ITMAX . . . . .	98	VIBration . . . . .	33
KKKMAX . . . . .	98	VICon . . . . .	32
LAYer . . . . .	44	VIPasa . . . . .	33
LENgth . . . . .	37	WAl1 . . . . .	46
LIINKing . . . . .	82	WAVelength . . . . .	37
LONGitudinal line supp. . . . .	64	WIDth . . . . .	39
LR . . . . .	98	XLOcation . . . . .	36
LS . . . . .	99	XSYM . . . . .	98

Figure 5.1 Alphabetic index to data groups and reset variables for VICONOPT data input (to be used in conjunction with the User Manual for VICONOPT, Release 1.1).

## 5.1 Program Control

This section covers the following keywords and data groups:

TITle	MODes
VICon	XLOCation
VIPasa	LENGth
BUCKling	WAVElength
VIBration	WIDth
ANALysis	FAST
DESIgn	PFAST
STAbilize on	GEOMetry
STAbilize OFF	ECHO on
NOSTabilize	ECHO OFF
EIGenvalues	NOEcho
TRIAL values	EXPLANation
ACCuracy	CHANGe set
MODal density	END

The following data input controls input, output and the various analysis and design options available.

**TITle**            The line following TITle will be printed in the data echo and will also appear on graphical output.

**VICon  $n_\epsilon$   $q$**       A single line of input, which causes a VICON analysis to be made using the values of  $\epsilon$  (see section 3.3.2, page 13) specified in the WAVElength data group (see page 38). If no values of  $\epsilon$  are specified in the WAVElength group, the program uses  $n_\epsilon$  values of  $\epsilon$  as follows: the first value is  $\epsilon = 1$ , the second value is  $\epsilon = 0$ , and the remainder are equally spaced between 0 and 1, starting with the highest. (Thus  $n_\epsilon = 1$  implies  $\epsilon = 1$  only, and  $n_\epsilon = 2$  implies  $\epsilon = 1$  and  $\epsilon = 0$  only.) If  $0 < \epsilon < 1$ , the program uses the  $(2q+1)$  values of  $\lambda$  implied by equation 3.1 with  $m = 0, \pm 1, \pm 2, \dots, \pm q$ . If  $\epsilon = 0$  or 1, then (except for repetitive analyses with  $0 < \eta < 1$ ) calculations are not required for

negative values of  $\lambda$  and the program uses the  $(q)$  values  $m = 0, 1, 2, \dots, (q-1)$ . For the exceptional  $0 < \eta < 1$  cases with  $\epsilon = 0$  and  $\epsilon = 1$ , the program uses the  $(2q-1)$  values  $m = 0, \pm 1, \pm 2, \dots, \pm(q-1)$  and the  $(2q)$  values  $m = 0, \pm 1, \pm 2, \dots, \pm(q-1), -q$  respectively. The default settings are  $n_\epsilon = 1$  and  $q = 5$ . Higher or lower values of  $q$  may be appropriate for particular problems, see section 3.3.2 (page 13).

VIPasa and VICON may both be selected on the same problem: results will be obtained for  $\lambda$  and  $\epsilon$  values selected in the Wavelength data group (see pages 37-38) for each particular analysis (or from  $n_\epsilon$  if applicable in a VICON analysis), and constraints such as point supports and supporting structure are ignored in the VIPASA analysis. If neither VIPasa or VICON is selected, VIPasa is assumed by default.

VIPasa	Causes a VIPASA analysis to be made, using the half-wavelengths $\lambda$ specified in the Wavelength data group (see page 37).
BUCKling VIBration	Causes buckling or vibration analysis to be used for the current problem. Only one type of analysis can be specified for a given problem. If neither analysis is selected, BUCKling is assumed by default. VIBration is only available in ANALYSIS problems.
ANALYSIS	Specifies an analysis problem, i.e. one for which no design changes are required.

<p>DESIGN n<sub>max</sub> n<sub>min</sub></p>	<p>A single line of input, specifying a design problem for which n<sub>max</sub> sizing cycles are to be performed unless the convergence criteria are satisfied sooner. At least n<sub>min</sub> sizing cycles will be performed regardless of the convergence criteria. Note that n<sub>min</sub> may be omitted if the value zero is required. Default n<sub>max</sub> = 6, n<sub>min</sub> = 0. If this DESIGN line is not present, an ANALYSIS is performed.</p> <p>DESIGN problems can only be solved with respect to BUCKling analysis. Some features (e.g. MODal density analysis) are not applicable to DESIGN problems, while others (e.g. FAST, PFAST, MODEs and PLOTting) only affect the initial analysis and/or the final analysis, as indicated under the respective headings elsewhere in chapter 5.</p>
<p>STABILize on</p>	<p>For a DESIGN problem, specifies that stabilization is to be performed during the sizing strategy as indicated in the flowchart of figure 4.1. For an ANALYSIS problem, stabilization will be performed following the analysis. Default is STABILize on for a DESIGN problem, STABILize OFF for an ANALYSIS problem.</p>
<p>STABILize OFF NOSTABILize</p>	<p>Either of these lines specifies that no stabilization is to be performed during the sizing strategy for a DESIGN problem, or following the analysis for an ANALYSIS problem.</p>

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```

## EIGenvalues data group

One line with any number of items of data.

Contains a list of desired eigennumbers. If this data is not input and only  $F_L$  is given in the TRIal values data (see below), the default of 1 is used.

TRIAL values  
 $F_L$   $F_U$

A single line of input giving trial values of the eigenparameter, as follows. If both  $F_L$  and  $F_U$  are given, they will be the initial estimates of the lowest and highest eigenvalues if the EIGenvalues data group is present (see above), they will be the range for which modal densities are found if the MODal density data is present (see page 36), and otherwise all eigenvalues in this range will be found. If only  $F_L$  is given, it will be the initial trial value for the eigenvalues listed in the EIGenvalues data. (If no EIGenvalues data is given, the first eigenvalue will be found.) Default  $F_L = 1$ .

ACCuracy  $x_t$

A single line of input, specifying the tolerance on the relative accuracy of eigenvalue calculation. Mode shapes and sensitivities cannot be found as accurately as the associated eigenvalues, and so when either of these additional calculations is requested (i.e. when MODE, PLOT or SENSitivities data is present, see pages 36, 91 and 81) the eigenvalues are calculated to a higher accuracy of  $TOLM * x_t$ , where TOLM is a RESet variable (see page 102). The default values  $x_t = 1.0 * 10^{-6}$  and  $TOLM = 1.0 * 10^{-3}$  are recommended for the majority of problems. Higher accuracy can often be achieved at little computational cost, but is sometimes limited by the onset of numerical ill-conditioning.

MODal  
density n<sub>DIV</sub>

The range of values given in the TRIal values data is divided into n<sub>DIV</sub> equal parts. No eigenvalues are found, but at each point of subdivision, the number of eigenvalues exceeded is determined, and modal densities are listed. This single line of input is distinguished from the MODes data by the presence of n<sub>DIV</sub>. (This option is only available in ANALYSIS problems.)

MODes

Causes mode shapes to be obtained and printed in a tabular format after all the required eigenvalues have been found. If graphical output is required, the PLOt data group (see page 91) should be used instead of the MODes data line. When finding all eigenvalues in a range given in the TRIal values data (see page 35), only one mode is found for any group of coincident eigenvalues. (In a DESign problem, mode shapes are only obtained following the final analysis.)

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XLOcation data group

One line containing any number of items of data.

This data is only used in a VICON analysis when mode shapes have been requested by the MODes or PLOt data (see above and page 91). It lists the values of x where the mode shape is calculated and printed or plotted. If this data is omitted, the program uses the single value  $x = \ell/2$  by default.

LENGth  $\ell$       A single line of input, giving the length  $\ell$  of the structure, i.e. the length of all plates. The length is required for VICON analysis and for VIPASA analysis when the half-wavelength  $\lambda$  is specified as  $\ell/\text{integer}$  in the WAVelength data (see below). Default 1.

```
*****  
      *  
      **  
***** Wavelength data group  
      **  
      *
```

Any number of lines containing any amount of data.

The data in this group prescribes the different axial half-wavelengths,  $\lambda$ , which are used in a VIPASA analysis (see section 3.3.1, page 12) and the values of  $\epsilon$  which control the  $\lambda$ 's used in a VICON analysis (see section 3.3.2, page 13). The different ways of prescribing these values are distinguished by the type and value of the first data input on each line (i.e. whether it is numeric or a character and the value of the character).

For a VIPASA analysis, three methods of input are available, as follows.

To prescribe a series of  $\lambda$ 's having the values  $\ell/j_1, \ell/j_2, \dots, \ell/j_n$ , use a line having triplets of data

$$+ \quad j_1 \quad j_n \quad j_{inc}$$

where  $j_1$  is the initial value of  $j$ , which is incremented by  $j_{inc}$  until  $j_n$  is passed. There can be any number of triplets on a line. When  $j_{inc}$  is the last item on a line and has the value unity, it may be omitted.

To prescribe a series of  $\lambda$ 's that have a constant ratio between adjacent ones, use the following

†      Ratio  $\lambda_1 \quad \lambda_2 \quad r$

where  $\lambda_1$  is the initial value of  $\lambda$  and  $\lambda_2$  is the limit on  $\lambda$ . Successive values of  $\lambda$  are obtained by multiplying by the ratio  $r$  until the limit is passed. There can be any number of such triplets on a line.

To prescribe a list of  $\lambda$  values, use the following

†      List  $\lambda_1 \quad \lambda_2 \quad \dots$

To prescribe a series of values of the parameter  $\epsilon$  used in a VICON analysis rather than the range indicated by  $n_\epsilon$  in the VICON data line (see page 32), use the line

†      Xi values  $\epsilon_1 \quad \epsilon_2 \quad \epsilon_{inc}$

where  $\epsilon$  takes the initial value  $\epsilon_1$  and is incremented by  $\epsilon_{inc}$  until the limit  $\epsilon_2$  is passed. The increment may be positive or negative. There may be any number of such triplets on a line.

Any type of WAVelength data can appear more than once and in any order. The calculations for the various  $\lambda$ 's will be done in the order they are generated in the WAVelength group. For example, consider the following WAVelength group:

```
WAVelength
4 10 2 1 3
R .08 .04 .75
List .02 .01
X 1. .79 -.05
```

In a VIPASA analysis if  $e = 1.$ ,  $\lambda$  will take the values .25, .16667, .125, .1, 1., .5, .33333, .08, .06, .045, .02, .01 .

For a VICON analysis,  $\epsilon$  will take the values 1., .95, .9, .85, .8 .

## WIDth P

Used only with repetitive analysis. A single line of input giving P, the number of repeating portions in the plate assembly (see figure 3.3(b)). For a closed section P should be given half this value (see section 3.4, page 17). The width may be entered as zero or the WIDth data may be omitted to indicate an infinitely wide plate assembly is to be considered. The value of P is used in conjunction with the TRANsverse wavelength data (see page 79) to determine the transverse half-wavelengths  $\lambda_T$  which will be considered in the repetitive analysis.

## FASt n

A single line of input, indicating the selection of the FASt option to reduce computation time by only calculating an eigenvalue if it is less than those previously found.

If  $n=1$ , the program will find the lowest eigenvalue for each value of  $\lambda$  in a repetitive VIPASA analysis and for each value of  $\epsilon$  in a repetitive VICON analysis, thus saving time by omitting unnecessary calculations for some values of  $g$  or  $\eta$ .

If  $n=2$ , the program will find the lowest eigenvalue for each change set, thus saving time by omitting unnecessary calculations for some values of  $\lambda$  or  $\epsilon$  (or for some combinations of  $\lambda$  or  $\epsilon$  and  $g$  or  $\eta$  for repetitive analysis).

If  $n=3$ , the program will find the lowest eigenvalue for the whole problem, i.e. the overall lowest for any change set.

If the FASt line is present and  $n$  is omitted or set to zero the program uses  $n=2$ . If no FASt line is given, all requested eigenvalues are found.

In a DESign problem, the FASt option operates as described above during the initial and final analyses, but has no effect on the

intermediate eigenvalue calculations during the sizing process. Eigenvalues omitted during the initial analysis are considered as usual during subsequent stabilization and sensitivity calculations.

#### PFASt n

A single line of input, indicating the selection of the PFAst option to reduce the amount of calculation and output, if mode shapes have been requested by the MODEs or PLOt data (see pages 36 and 91), by only obtaining, printing and plotting mode shapes for the lowest eigenvalues found. (Note that PFAst operates independently of the FAST option, see page 39.)

If  $n=1$ , the program will obtain and print or plot the mode of the lowest eigenvalue found for each value of  $\lambda$  in a repetitive VIPASA analysis and for each value of  $\epsilon$  in a repetitive VICON analysis.

If  $n=2$ , the program will obtain and print or plot the mode of the lowest eigenvalue found for each change set.

If  $n=3$ , the program will obtain and print or plot the mode of the lowest eigenvalue for the whole problem, i.e. the overall lowest for any change set.

If the PFAst line is present and  $n$  is omitted or set to zero the program uses  $n=2$ . If no PFAst line is given, all modes are obtained and printed or plotted.

In a DESign problem, the PFAst option only affects the final analysis.

#### GEOmetry

No analysis is performed, but the panel geometry is calculated and checked. Also a plot of the undeformed structure cross-section is made if plotting is called for in the PLOt data (see page 91). This option is useful for checking input data for a new problem.

ECHO on	Input data after this line will be printed in the output exactly as entered and will also be printed in an organized listing with descriptive headings.
ECHO OFF NOEcho	Either of these lines turns off printing of input data subsequent to where the line is inserted, including the organized listing. Default is ECHO on.
EXPlanation	Causes explanatory headings to be printed at the beginning of major tables of data appearing in the data echo.
CHAnge set n	A single line of input, to signal the start of a new change set in the current problem. n is a positive integer which will be used to identify the change set in the printed output. If n is omitted the program will provide a number, which will be negative (-1 for the first occurrence of CHAnge set data, -2 for the second occurrence, etc.) in order to avoid duplication of positive numbers supplied elsewhere by the user. Further information about the use of change sets is given in section 5.13 (see page 104).
END	Signals the end of data for the current problem. Additional problems may be entered, each followed by END.

## 5.2 Plate Description

This section covers the following data groups:

MATerial  
LAYer  
WALL  
PLate

The following data groups are used to define the basic plates from which the plate assembly is generated.

The most usual way of defining a plate starts with a list of the material properties (there may be more than one material in a given plate), then the thickness and orientation of the material in each layer, how the layers are stacked to form a wall and finally, a plate is defined as a wall of specified width and in-plane loading. There is no input of nodal coordinates, simply plate breadths and (by subsequent data groups defined in sections 5.4 and 5.5, see pages 53-63) their orientation and connectivity. The coordinates resulting from the input are calculated and printed. Warning and fatal diagnostic messages are printed if input results in inconsistent geometry. Plots of the cross-section may also be obtained as an aid to checking input (see pages 89-92). When preparing data for a new problem, the user may wish to restrict the operation of the program to checks of the input and panel geometry by using the GEOMETRY option (see page 40).

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  ** **
    *   *

```

MATerial data group

Any number of lines, each containing 8 items of data.

Data required unless all WALL data given as Anisotropic plates.

This gives the orthotropic material properties used in the individual layers of the various walls of the plate assembly. There is one line for each different material. For an isotropic material only  $n_M$ ,  $E_1$  (i.e.  $E$ ),  $\nu_{12}$  (i.e.  $\nu$ ) and  $\rho$  need be entered.

## Item

- |   |            |   |
|---|------------|---|
| 1 | $n_M$      | MATerial reference number, i.e. the number referenced by item 3 in the LAYer data (see page 44) or item 4 in the WALL data for Isotropic plates (see page 46). Must be different from all other MATerial reference numbers. |
| 2 | $E_1$      | Young's modulus in direction of axis 1.   |
| 3 | $\nu_{12}$ | Poisson's ratio, such that $\nu_{12} E_2 = \nu_{21} E_1$ .  |
| 4 | $\rho$     | Density (mass/volume).  |
| 5 | $E_{12}$   | In-plane shear modulus.<br>(Zero causes $E_{12} = \frac{E_1}{2(1 + \nu_{12})}$ .)   |
| 6 | $E_2$      | Young's modulus perpendicular to axis 1.<br>(Zero causes $E_2 = E_1$ .)   |
| 7 | $\alpha_1$ | Coefficient of thermal expansion in direction of axis 1.  |
| 8 | $\alpha_2$ | Coefficient of thermal expansion in direction perpendicular to axis 1.  |

The above data is repeated for each material required. If  $\nu_{12}$  is omitted, the value zero is used.  $\rho$  is vital in all design problems and in vibration analysis problems. The only penalty for omitting it in buckling analysis problems is that the mass of the structure, which is given in the output, omits all plates formed from this material.  $\alpha_1$  and  $\alpha_2$  are only required for laminated plates whose longitudinal loads are to be determined from uniform strains or total loads on the plate assembly (see the AXIAL loading data group, page 52) and for which thermal effects are to be taken into account (see also items 5 and 6 in the LAYer data, page 44).

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      **
*****
      **
      *

```

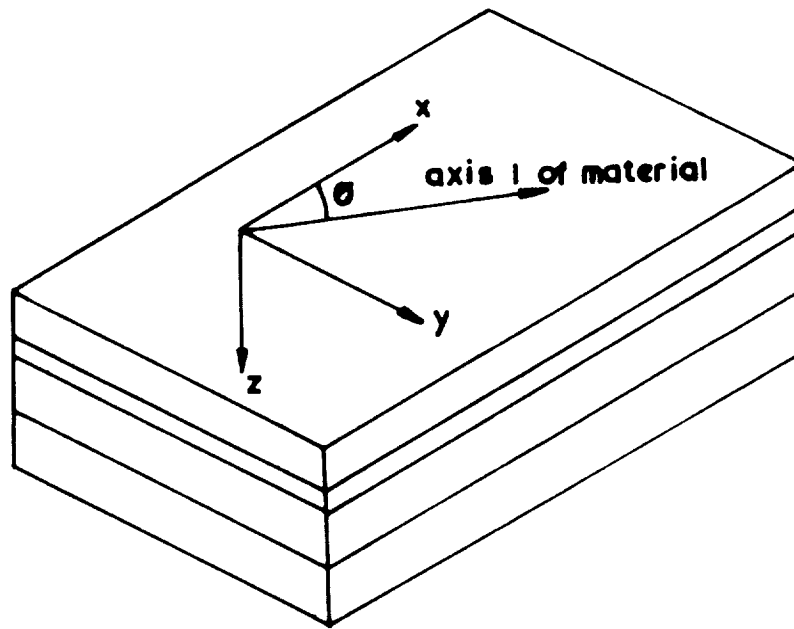
## LAYer data group

Any number of lines, each containing 6 items of data.

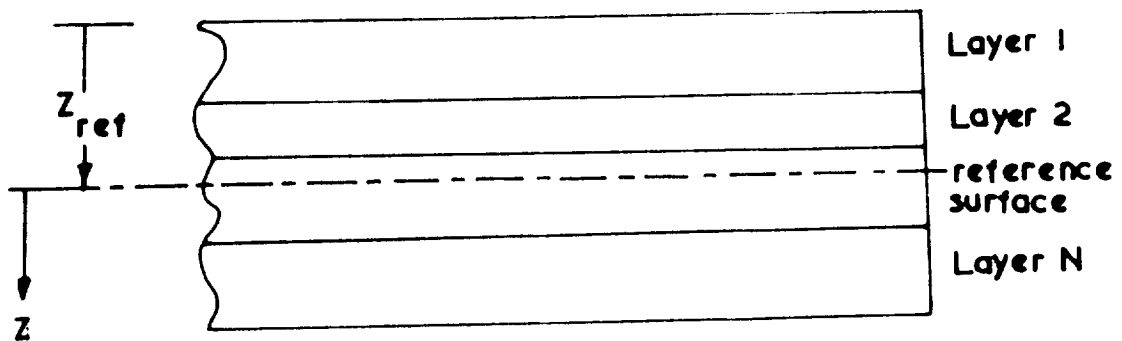
## Item

- |   |          |   |
|---|----------|---|
| 1 | $n_L$    | LAYer reference number, i.e. the number referenced by items 2, 3, ..., $n_{Li}$ in the WALL data for laminated walls (see page 48). Must be different from all other LAYer reference numbers. |
| 2 | $h$      | Layer thickness.  |
| 3 | $n_M$    | MATerial reference number, see page 43.   |
| 4 | $\theta$ | Ply angle, i.e. the angle (in degrees) between material axis 1 and the x (longitudinal) axis of the plate, with the positive sense defined by figure 5.2(a).                                  |
| 5 | $T_V$    | Variable component of temperature of layer (VICONOPT multiplies this by the eigenparameter, F.)   |
| 6 | $T_F$    | Fixed component of temperature of layer (so temperature is $T_F + FT_V$ ).  |

The above data is repeated for each layer required.  $T_V$  and  $T_F$  are only required if longitudinal loads are to be determined from uniform strains or total loads on the plate assembly (see the AXIAL loading data group, page 52) and thermal effects are to be taken into account (see also items 7 and 8 in the MATerial data, page 43). Otherwise  $T_V$  and  $T_F$  should be set to zero or omitted.



(a)



(b)

Figure 5.2 Layered wall, showing (a) direction of material axis 1 and (b) layer stacking sequence and location of reference surface, i.e.  $z_{ref}$  below the upper surface of the wall.

```

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    * * * *
  * * * * *
    * * *
      *   *

```

## WALl data group

Any number of lines, each with at least 2 items of data.

Used to describe the characteristics of each wall. There are three ways of doing this and each wall can be specified in any of the ways regardless of its reference number and of its position in the list of WALl data. The first way is for isotropic plates and involves four items of data. The second way gives the [A] and [D] matrices for an anisotropic or orthotropic plate and involves between eleven and thirteen items of data. The third way specifies a laminated wall by identifying its layers. (This is likely to be the most useful way, particularly since it gives an alternative way of specifying an isotropic plate by means of a wall with one isotropic layer.)

Isotropic plates

†      I  $n_W$  t  $n_M$

## Item

- |   |       |   |
|---|-------|---|
| 1 | I     | Type Iso (or just I) indicating this is an isotropic plate.   |
| 2 | $n_W$ | WALl reference number, i.e. the number referenced by item 3 of the PLate data (see page 49). Must be different from all other WALl reference numbers.   |
| 3 | t     | Plate thickness.  |
| 4 | $n_m$ | MATerial reference number (see page 43). (Only $E_1$ , $\nu_{12}$ and $\rho$ are taken from the MATerial list and blank causes the default $n_M = 1$ ). |

Anisotropic plates

†		A $n_W$ $\gamma$ $A_{11}$ $A_{12}$ $A_{22}$ $A_{33}$ $D_{11}$ $D_{12}$ $D_{22}$ $D_{33}$ $D_{13}$ $D_{23}$										
Item												
1	A	Type Aniso (or just A) indicating this is an anisotropic plate.										
2	$n_W$	WALL reference number, i.e. the number referenced by item 3 of the PLate data (see page 49). Must be different from all other WALL reference numbers.										
3	$\gamma$	Mass per unit of surface area of plate.										
4-7	$A_{11}, A_{12}, A_{22}, A_{33}$	Terms from the in-plane membrane stiffness matrix [A].										
8-13	$D_{11}, D_{12}, D_{22}, D_{33}, D_{13}, D_{23}$	Terms from the out-of-plane bending stiffness matrix [D].										

If  $D_{13} = D_{23} = 0$ , orthotropic plate theory is used to save computation time. Item 3 is vital in all design problems and in vibration analysis problems. The only penalty for setting it to zero in buckling analysis problems is that the mass of the structure, which is given in the output, will omit all plates formed from this wall.

Laminated walls

†	$n_W \ n_{L1} \ n_{L2} \ \dots \ n_{Ln}$	General wall with $n$ layers
†	$n_W \ n_{L1} \ n_{L2} \ \dots \ n_{Ln} \ S$	Symmetric wall with $2n$ layers
Item		
1	$n_W$	WALl reference number, i.e. the number referenced by item 3 of the PLAtE data (see page 49). Must be different from all other WALl reference numbers.
2,3,...	$n_{Li}$	LAYer reference numbers (see page 44) of the wall in sequence starting at the upper surface of the wall (see figure 5.2(b)). If input with reversed sign, i.e. as negative, the sign of $\theta$ used is the reverse of that given in the LAYer data.
$n+2$	$S$	If the wall is symmetric, input only the upper half of the wall followed by letter S.

Thus the layers are stacked in sequence in the direction of increasing  $z$ . The program is only strictly correct when the [A] matrix is orthotropic and the [B] matrix is null, as is the case for balanced symmetric laminates, but the user can specify all the layers through the whole thickness if desired, by omitting "S" and continuing until all layers have been input. (An isotropic wall can be obtained by using an appropriate single layer.) Such specification of all layers is necessary when the LAYer data is used to represent a through thickness temperature gradient. If a [B] matrix results from specifying all the layers, it is ignored in the analysis. In addition the reference surface is not in general at the middle surface. See Appendix 1 (page 150) for a discussion of how the location of the reference surface is determined and how the [D] matrix may be modified to yield a potentially more accurate result.

```

      *  *
    *  *  *
  *  *  *  *
*** *  *  *  *
    *  *  *
      *  *

```

## PLAte data group

Any number of lines each containing 6 items of data.

Used to describe the characteristics of each plate. The integers of items 3, 4 and 5 refer to the reference numbers of the indicated data groups.

## Item

- |   |       |   |
|---|-------|---|
| 1 | $n_p$ | Plate number. (Positive integer, $\leq 120$ . Must not duplicate a plate or substructure number used elsewhere in data.)  |
| 2 | $b$   | Plate breadth.  |
| 3 | $n_W$ | WAl1 reference number (see pages 46-48). If input with reversed sign, i.e. as negative, the values of $D_{13}$ and $D_{23}$ (given by the WAl1 data for Anisotropic plates or calculated by the program for laminated walls) are ignored. |
| 4 | $n_N$ | STress resultant reference number (see page 50). Enter zero if the plate is unloaded or if its loading is defined entirely by the AXIal loading data (see page 52).   |
| 5 | $n_F$ | FOUndation reference number (see page 67). Enter zero if the plate does not have an elastic foundation.   |
| 6 | $n_g$ | Number of times the plate is to be subdivided in order to calculate the perturbation stress levels (see page 90). Enter zero if stress levels are not to be calculated, or if they are to be calculated without subdividing the plate.    |

## 5.3 Plate In-plane Loading

This section covers the following data groups:

STress resultant  
AXIal loading

The user is required to supply data so that the in-plane loading in each plate is determined. This is accomplished by the STress resultant and/or the AXIal loading data groups as follows. Loadings are a combination of live (variable) and dead (fixed) values where the live load is factored by the load factor in a buckling problem and ignored in a vibration problem. Shear and transverse loads must be entered explicitly in the STress resultant group. Longitudinal loads may also be entered in this way, or may be calculated by the program from values entered in the AXIal loading group which give a uniform strain or a total longitudinal load on the plate assembly.

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\*

STress resultant data group

Any number of lines each containing 7 items of data.

Gives the values of the longitudinally invariant, in-plane, forces per unit length of plate edge. ( $N_L$  for longitudinal compression,  $N_S$  for shear,  $N_T$  for transverse compression. See figure 2.1, which also gives the positive direction of  $N_S$ .)

## Item

- |   |          |   |
|---|----------|---|
| 1 | $n_N$    | Stress resultant number, i.e. the number referenced by item 4 of the PLate data (see page 49). Must be different from all other stress resultant reference numbers. |
| 2 | $N_{LL}$ | Live load component of $N_L$ .  |
| 3 | $N_{SL}$ | Live load component of $N_S$ .  |

- 4      $N_{TL}$      Live load component of  $N_T$ .
- 5      $N_{LD}$      Dead load component of  $N_L$ .
- 6      $N_{SD}$      Dead load component of  $N_S$ .
- 7      $N_{TD}$      Dead load component of  $N_T$ .

Buckling problems are solved for  $N_L = N_{LD} + FN_{LL}$ ,  $N_S = N_{SD} + FN_{SL}$  and  $N_T = N_{TD} + FN_{TL}$ , where  $F$  is the load factor which is common to all plates and for which the program finds the value when buckling occurs. In vibration problems  $N_{LD}$ ,  $N_{SD}$  and  $N_{TD}$  define the stress state for which the natural frequencies are found and  $N_{LL}$ ,  $N_{SL}$  and  $N_{TL}$  are ignored, so that the above input scheme involves items 2-4 being given the value zero (or dummy values) for every plate.

If total longitudinal live and dead loads on the plate assembly are specified in the AXIAL loading data group (see page 52), all values of  $N_{LL}$  and  $N_{LD}$  given in the STRESS resultant group will be replaced by values implied by the distribution of these total longitudinal loads among the individual plates of the assembly. If longitudinal loads are to be calculated by the program from uniform strains specified in the AXIAL loading data group, any zero values of  $N_{LL}$  or  $N_{LD}$  given in the STRESS resultant data group will be replaced by values calculated from such strains, but non-zero values will not be so replaced.

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AXIal loading data group

One line containing text and 2 items of data.

The longitudinal plate loads may be determined from a uniform strain or a total load on the plate assembly. To specify a strain input, use:

†      Epsilon  $\epsilon_L$   $\epsilon_D$

where the subscripts L and D denote live and dead values of strain.

To specify a load input, use:

†      Load  $P_L$   $P_D$

where the subscripts L and D denote live and dead loads.

Any thermal effects specified by items 7 and 8 of the MATERIAL data (see page 43) and by items 5 and 6 of the LAYER data (see page 44) are taken into account in these load calculations. If fixed temperatures are input in the LAYER data, it may be necessary to specify tensile (negative) fixed strains or loads to prevent buckling at zero value of factor F.

## 5.4 Plate and Substructure Alignment, including Cylindrical Axes

This section covers the following data group:

### ALIgnment

Because the geometry of the plate assembly is completely defined in two dimensions it is possible to define all the relevant information very concisely by giving just the plate breadths, their orientation (i.e. their angular position), the manner in which they are linked together and any offsets between plate reference surfaces at points of connection. A large part of this geometric definition is accomplished in the ALIgnment data group, in which the plates and substructures that are used subsequently in the CONnection and ATTachment data (see section 5.5, pages 61-63) are defined.

```

      *   *
    **   **
  *****
    **   **
      *   *

```

### ALIgnment data group

Consisting of rotation, offset, substructure and cylindrical axes data. Any number of lines, with text on some.

Required unless all plates are collinear.

Four separate types of data instructions are included in this group. They handle: (1) rotation of plates or substructures; (2) offsets of the ends of plates or substructures; (3) linking together of plates or substructures to form new substructures; and (4) defining plates or substructures in terms of cylindrical axes instead of the more usual Cartesian ones.

The above operations can be performed in any order or combination to repeatedly redefine a plate or substructure into a series of different plates or substructures having various combinations of offsets, rotations and Cartesian or cylindrical axes systems, although care is required to understand the consequences of a specific series of such operations.

Originally all plates created by the PLate data (see page 49) are aligned with their reference surface in the xy plane, the y axis in the direction of the plate width and the z axis normal to the plate reference surface, see figures 2.1(b) and 5.3(a). The x, y, z axes form a right handed system which defines the directions of displacements u, v and w. The x direction is always along the plate assembly length. Rotations and cylindrical coordinate transformations alter the local y and z directions of plates and substructures. Each node of the plate assembly has its own y and z axes (in which mode shape deflections are measured), and these remain in the same directions for all nodes unless cylindrical coordinate transformations are used.

Rotation (part of ALIgnment data)

Each line of Rotation data gives a plate or substructure its correct alignment on a cross-section view of the plate assembly, i.e. it defines the angle  $\mu$  of figure 5.3(b).

+ R P<sub>n</sub> P<sub>o</sub>  $\mu$

Item

- |   |                |   |
|---|----------------|---|
| 1 | R              | Type Rotate (or just R) to indicate a plate is to be rotated.   |
| 2 | P <sub>n</sub> | Reference number of new, i.e. rotated, plate or substructure. Must not duplicate a plate or substructure number used elsewhere in data.   |
| 3 | P <sub>o</sub> | Reference number of old, previously defined, plate or substructure which is rotated to give P <sub>n</sub> . P <sub>o</sub> and P <sub>n</sub> must be both doubly connected ( $\leq 120$ ) or both singly connected ( $> 120$ ). |

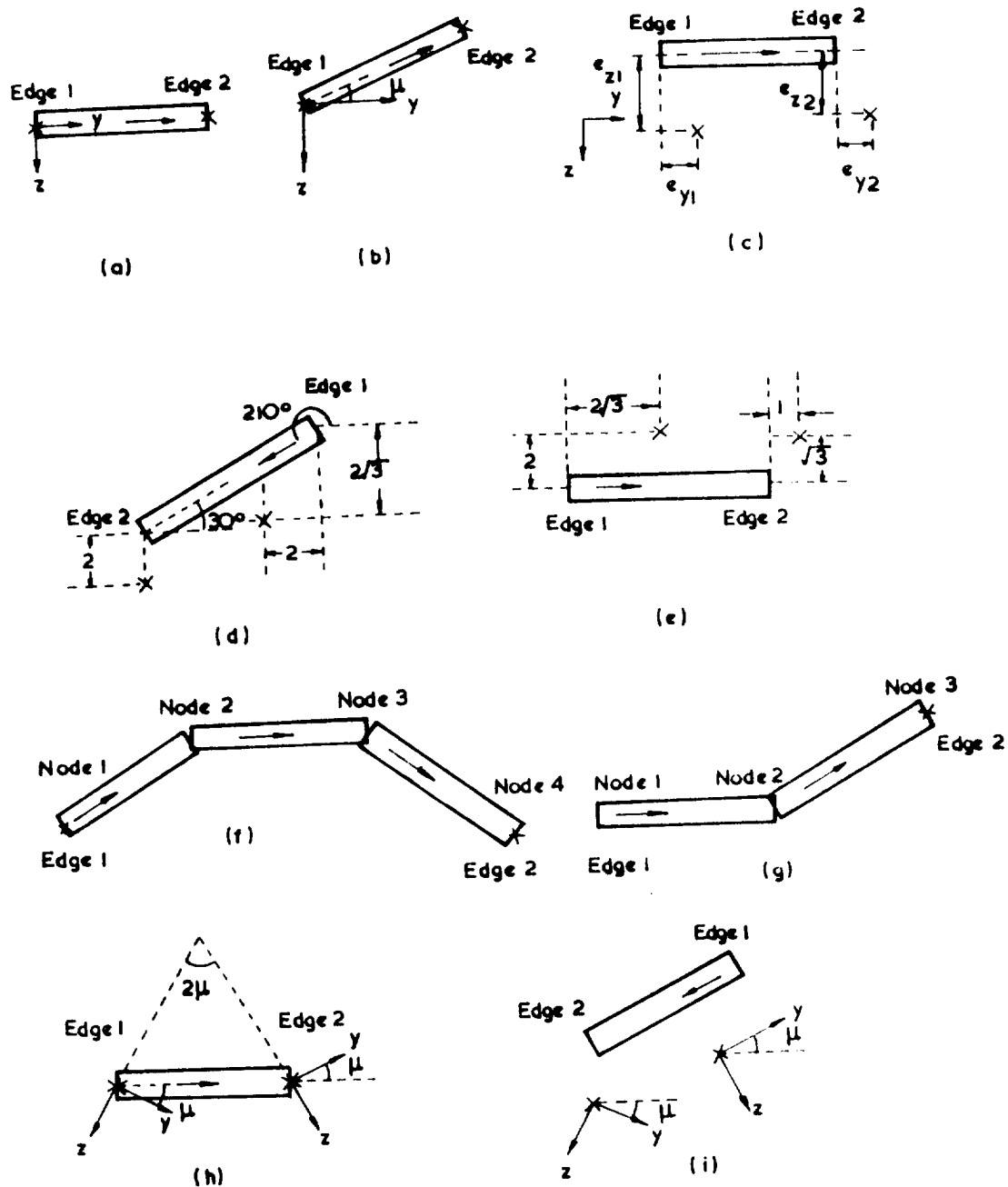


Figure 5.3 Definitions and examples for plate alignment options. Connection nodes are denoted by crosses, and arrows indicate the direction from edge 1 to edge 2 of each plate. (a) Original plate. (b) Rotation. (c) Addition of offsets. (d) Example showing addition of offsets after rotation by  $210^\circ$ . (e) The offsets of (d) can alternatively be obtained by adding these offsets to the unrotated plate and then rotating by  $\mu = 210^\circ$ . (f) Doubly connected substructure. (g) Singly connected substructure. (h) Transformation to cylindrical coordinates. (i) Example showing cylindrical coordinate transformation of the rotated plate with offsets shown in (d).

- 4       $\mu$       Anti-clockwise angle of rotation in degrees between y axis and a straight line originating at edge 1 and connecting to edge 2, see figure 5.3(b).

CAUTION: The LAYers and the STress resultants (see pages 44 and 50) are rotated with the plate, with the implications discussed in section A2.3 of Appendix A2 (see page 155).

Offset (part of ALIgnment data)

Each line of Offset data adds offsets in the y and z directions at the longitudinal edges of any plate or substructure.

†      0 P<sub>n</sub> P<sub>o</sub> e<sub>y1</sub> e<sub>z1</sub> e<sub>y2</sub> e<sub>z2</sub>

Item

- |     |  |   |
|-----|--|---|
| 1   | 0  | Type Off (or just 0) to indicate this is an offset.   |
| 2   | P <sub>n</sub>   | Reference number of new plate or substructure, i.e. after offsets added. Must not duplicate a plate or substructure number used elsewhere in data.  |
| 3   | P <sub>o</sub>   | Reference number of old, previously defined, plate or substructure to which offsets are added to give P <sub>n</sub> . P <sub>o</sub> and P <sub>n</sub> must be both doubly connected ( $\leq 120$ ) or both singly connected ( $> 120$ ).   |
| 4-7 | e <sub>y1</sub><br>e <sub>z1</sub><br>e <sub>y2</sub><br>e <sub>z2</sub> | The offsets (i.e. eccentric connections) in the y and z directions, at longitudinal edges 1 and 2 respectively, of a plate or doubly connected substructure, with the positive direction taken from the edge to the node, see figure 5.3(c). Similarly e <sub>y1</sub> and e <sub>z1</sub> are the offsets of the connection node of a singly connected substructure. |

Figures 5.3(d) and 5.3(e) illustrate the use of Rotation and Offset data and show how the same physical situation can be modelled either by rotating the plate first or by adding the offsets first. Suppose that the plate number prior to rotation is 6 and that it is desired to number it 11 after the rotation and offsets (or vice-versa) have been applied. Then the data corresponding to figure 5.3(d) is

```
ROT  7 6 210.0
OFF 11 7 -2.0 3.464 0 2.0
```

whereas that for figure 5.3(e) is (typing O and R for Offset and Rotate)

```
O    7 6    3.464 -2 1 -1.732
R    11 7    210
```

where a plate with number 7 has been introduced at the intermediate stage in both cases, although of course it is not the same plate in the two cases.

#### Substructure (part of ALIgnment data)

A full description of the types of substructures which can be created by the ALIgnment data is given in Appendix 2 (see pages 152-163), which also gives illustrative examples, including the use of cylindrical axes. Simple examples are shown, in figure 5.3(f) for a doubly connected substructure with  $N_{\text{sub}} = 4$  nodes, and in figure 5.3(g) for a singly connected substructure with  $N_{\text{sub}} = 3$  nodes. It should be noted that, although the use of substructures is often advisable because they can yield much briefer data and much quicker solutions, all problems can be solved without using substructures if the user so wishes. The rules for preparing the data for substructures are as follows.

†         $P_n P_o \dots$

#### Item

1         $P_n$         Substructure number. Positive integer  $\leq 899$ .  
If  $\leq 120$ , doubly connected; if  $\geq 121$ , singly  
connected. Must not duplicate a plate or  
substructure number used elsewhere in data.

set i        Given in the order set 1, set 2, ..., set  
 $N_{\text{sub}}$ . Set i relates to node i of the chain  
of nodes forming the substructure (see page  
152).

#### Item for set i

1         $P_o$         Reference number ( $\leq 120$ ) of any previously  
defined plate or doubly connected  
substructure connecting node i to node i + 1.  
Edge 1 of the plate or substructure must be  
at node i.

2         $-P_{o1}$         If other previously defined plates or doubly  
connected substructures also connect nodes i  
and i + 1, their reference numbers are given  
with reversed sign (i.e. negative integers  
 $\geq -120$ ).

or         $P_{o2}$         If any previously defined singly connected  
substructures are connected to node i, their  
reference numbers ( $> 120$ ) are given.

or         $900+n_s$         If there is a longitudinal line support at  
node i, the integer given here is 900 plus  
its reference number in the LONGitudinal line  
supports data (see page 65). Thus the  
integer 903 indicates the presence of the  
line support defined by the third line in the  
LONGitudinal line supports input.

3,4,...        As item 2, with items continuing to be given  
(in any order) until all data relating to  
node i has been given.

When node  $N_{sub}$  has singly connected substructures and/or longitudinal line supports connected to it, enter 0 (i.e. zero) as item 1, then the appropriate values for items 2, 3, etc.

CAUTION: A LONGitudinal line support which includes rigid or very stiff supports must not be placed at a connection node of a substructure (i.e. node  $N_{sub}$  for any substructure or node 1 for a doubly connected substructure) if that substructure is subsequently going to be rotated or offset by ALIgnment data. However this rule can be ignored if the line support involves only elastic stiffnesses of ordinary order.

When several plates or substructures are connected to form a new substructure, they are connected with yz axes aligned. If two or more plates or substructures connect two nodes as indicated by a minus sign in the data the coordinates and the direction of the yz axes of the second point as determined by all the connections should match. If these matches are not achieved within a certain user specified tolerance (see TOLG in the RESet data group, page 102), a non-fatal diagnostic message indicating the amount of error is printed. If they are not matched to a coarser tolerance, the program terminates.

#### Cylindrical coordinate transformation (part of ALIgnment data)

Cylindrical axes may be defined by rotating the yz axes in opposite directions by the angle  $\mu$ , as shown in figure 5.3(h). A series of plates with cylindrical axes can be joined together by the substructure data (as shown in figure A2.3(a) of Appendix 2) to approximate a circular arc to any desired tolerance by varying the number of plates. The details of this capability and examples which show how powerfully it can be applied are given in Appendix 2 (see pages 158-163). The input is

†	C P <sub>n</sub> P <sub>o</sub> $\mu$	
Item		
1	C	Type Cyl (or just C) to indicate this is a cylindrical coordinate transformation.
2	P <sub>n</sub>	Reference number of new plate or substructure, i.e. after cylindrical coordinate transformation. Must not duplicate a plate or substructure number used elsewhere in data.
3	P <sub>o</sub>	Reference number of old, previously defined, plate or substructure which is transformed into P <sub>n</sub> . P <sub>o</sub> and P <sub>n</sub> must be both doubly connected ( $\leq 120$ ) or both singly connected ( $> 120$ ).
4	$\mu$	Clockwise angle of rotation of yz axes at edge 1 in degrees. The yz axes at edge 2 undergo the opposite rotation.

Note that the rotation is measured from the present location of the yz axes. Thus a plate or substructure defined with cylindrical axes with angle  $\mu$  can be restored to the standard global axes by using the cylindrical data with angle  $-\mu$ . Note too that cylindrical axes are not needed for singly connected substructures because only one connection node is involved. If a plate has been given offsets, transformation to cylindrical coordinates is done by rotating the yz axes at the nodes and not at the plate ends, as shown in figure 5.3(i). The effect of previous rotation is also shown in this figure.

### 5.5 Assembly of Final Structure

This section covers the following data groups:

CONNECTION  
ATTACHMENT

The final structure is assembled from plates and/or substructures and longitudinal line supports by means of CONNECTION and/or ATTACHMENT data input, as follows.

Number each node (i.e. each longitudinal junction between plates and/or substructures, plus free longitudinal edges of plates or doubly connected substructures) of the structure consecutively, starting from 1 and excluding internal nodes of substructures (i.e. the nodes referred to in Appendix 2, see page 152, as 1, 2, ..., ( $N_{\text{sub}}-1$ ) when preparing singly connected substructure data or as 2, 3, ..., ( $N_{\text{sub}}-1$ ) when preparing doubly connected substructure data). This numbering should be chosen so as to minimize the greatest difference in node numbers of any pair of nodes which are connected by a plate or doubly connected substructure, so that the stiffness matrix bandwidth is reduced to save computation time and storage.

The final plate assembly is defined by two data groups. The CONNECTION data defines the connections between nodes formed by plates and doubly connected substructures. The ATTACHMENT data defines longitudinal line supports and singly connected substructures that are attached at individual nodes. Appendix 2 (see pages 152-163) contains examples of the CONNECTION and ATTACHMENT data for specific problems and illustrates the relation to the PLATE and ALIGNMENT data.

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  * * * * *
    * * *
      *   *

```

## CONnection data group

Any number of lines each containing any number of triplets of integer data.

Required unless assembly is done with ATTachment data alone.

The format is similar to that of connection lists in many finite element programs. Thus the first two numbers of the triplet are the nodes being connected with the first number being the lower numbered node. The third number of the triplet is the plate or doubly connected substructure number. The triplets can normally be given in any order (but see the warning on page 93 concerning the use of the NODEs data when stress level plots are requested), and each node number appears once for each connection which involves that node. It is essential that the PLate and ALIgnment data (see pages 49 and 53-60) give all the plates and substructures their proper orientations and dimensions, including the requirement that edge 1 of a plate or substructure (see figure 5.3) must correspond to the lower numbered node in the triplet. An example is given in Appendix 2 in connection with figure A2.2 (see page 157).

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      *
***** *
      *
      *
      *

```

## ATTachment data group

Any number of lines each containing any number of doublets of integer data.

The first item of each doublet is a node number which has either a line support or a singly connected substructure attached to it. If a singly connected substructure is attached, the second item of the doublet is the substructure number. It is essential that the ALIGNment data (see pages 53-60) gives the substructure its proper orientation and dimensions, including the requirement that its node  $N_{\text{sub}}$  (see page 152) represents its point of attachment to the panel. If a line support is present, the second item of the doublet is the integer 900 plus the reference number of the line support which appears in the LONGitudinal line supports data (see page 65). Thus the integer 903 indicates the presence of the line support defined by the third line in the LON data input. The doublets can be given in any order and each node appears once for each attachment at that node.

## 5.6 Line Supports, Point Supports and Elastic Foundations

This section covers the following data groups:

LONGitudinal line supports  
POInt supports  
FOUndations

This section firstly describes the LONGitudinal line supports which may be attached to nodes of substructures (see the ALIGNment data group, pages 57-59) or to nodes of the final plate assembly (see the ATTachment data group, page 63). It next describes the attachment of POInt supports to nodes of the final structure which is a key feature of the VICON-type analysis. Finally, it describes the addition of elastic (Winkler) FOUndation stiffnesses to individual plates, of which further details are given in reference 14.

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*****
      **
      *
LONGitudinal line supports data group

```

One or more lines each with 5 items of data.

Each line of the LONGitudinal line supports data has the form that follows and prescribes a longitudinal line support which restrains any combination of the four degrees of freedom at a node (i.e. any of  $u$ ,  $v$ ,  $w$  and  $\psi$ , see figure 3.1(b)).

### Item

- 1 An integer with between one and four digits each lying between 1 and 4, inclusive. These digits can be given in any order and identify the position of the degree of freedom in the list (1= $u$ , 2= $v$ , 3= $w$ , 4= $\psi$ ).

2,3,... List of elastic stiffnesses per unit length which are applied in order to the degrees of freedom identified by the successive digits of item 1. A zero is used to indicate the infinite stiffness of a rigidly supported freedom. Thus the list must contain one real number for each such digit of item 1 except that zeros at the end of the list can be omitted.

For example, the data

LON  
241 26.5

resists the v displacement (see figure 3.1(b)) with stiffness per unit length of 26.5 units, prevents rotation and longitudinal displacement, and leaves the w displacement unrestrained. Note that the unrestrained freedom was obtained by omitting it from the digits of item 1 and that it could not be obtained by specifying a zero stiffness per unit length because zero is interpreted as a rigid support.

NOTE: The LONGitudinal line supports group is also used to define supports which will be attached to beam substructures and to final supporting structures (see the descriptions of the BALignment and SUPporting structures groups in section 5.7, pages 72 and 75). In these cases, each line has up to 4 items of data: item 1 comprises up to 3 digits each lying between 2 and 4 inclusive, identifying the degrees of freedom (2=v, 3=w, 4=ϕ); and items 2-4 are interpreted as the stiffnesses of point supports rather than the stiffnesses per unit length of line supports.

```

      *
    * *
  * * *
*****
  * * *
    * *
      *

```

## POInt supports data group

Any number of sets of 2 or 3 lines.

The VICON analysis permits rigid or elastic point supports to be introduced at any node of the final plate assembly, at any longitudinal coordinate  $x$  ( $0 \leq x < \ell$ ), see section 3.2 (page 9). The plate assembly is then analyzed as infinitely long, with these point supports repeated at longitudinal intervals of  $\ell$ . Each point support can be specified as restraining any combination of the four degrees of freedom at the node (i.e.  $u$ ,  $v$ ,  $w$  and  $\psi$ , see figure 3.1(b)) but solution time grows rapidly with the number of freedoms constrained and so freedoms which are known to be of minor importance should not be constrained. Point supports cannot be introduced at internal nodes of substructures.

Each set of data comprises up to 3 lines (of which the third may be omitted), which must appear in the following order.

Item, on line 1 (5 items of data)

- 1           An integer with between one and four digits which each lie between 1 and 4, inclusive. These digits can be given in any order and identify the position of the degree of freedom in the list (1= $u$ , 2= $v$ , 3= $w$ , 4= $\psi$ ).
- 2,3,...    List of elastic stiffnesses which are applied in order to the degrees of freedom identified by the successive digits of item 1. A zero is used to indicate the infinite stiffness of a rigidly supported freedom. Thus the list must contain one real number for each such digit of item 1 except that zeros at the end of the list can be omitted.

Item, on line 2 (One or more items of data)

1,2,... List of nodes at which the constraints of line 1 are applied.

Item, on line 3 (Two or more items of data, if present)

1	X	Type X (or X =).

2,... List of values of  $x$  for all of which the constraints of line 1 are applied at the nodes of line 2. (This line can be omitted when only  $x = 0$  is wanted.)

Additional constraints can be given on further such sets of lines. Note that line 1 is similar to a line of LONGitudinal line supports data (see page 65).

```

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  ***
*****
  ***
    **
    *
FOUndations data group

```

Any number of lines each containing 3 items  
of data.

The FOUNDATIONS data group describes the elastic foundations which may be applied to plates. Out-of-plane ( $k_z$  in the  $z$  direction) and in-plane ( $k^*$  in the  $x,y$  plane) Winkler foundation stiffnesses are included, with the latter restricted to be the same for all directions in the plane.

Item

1	$n_F$	FOUndation reference number, i.e. the number referenced by item 5 of the PLate data (see page 49). Must be different from all other FOUndation reference numbers.
2	$k_z$	Out-of-plane Winkler foundation stiffness per unit area.
3	$k^*$	In-plane Winkler foundation stiffness per unit area.

## 5.7 Beam-Column Supporting Structures

This section covers the following data groups:

BEAMs  
BALignment  
SUPporting structures

The VICON analysis permits supporting structures, each comprising an assembly of beam-columns lying in the  $yz$  plane, to be attached to any set of nodes of the final plate assembly, at any longitudinal coordinate  $x$  ( $0 \leq x < \ell$ ), see section 3.2 (page 9). The plate assembly is analyzed as infinitely long, with these supporting structures repeated at longitudinal intervals of  $\ell$ . Each attachment of a supporting structure to a node of the plate assembly can be specified as constraining any combination of the three in-plane degrees of freedom at the node (i.e.  $v$ ,  $w$  and  $\psi$ , see figure 3.1(b)) but solution time grows rapidly with the number of freedoms constrained and so freedoms which are known to be of minor importance should not be constrained. Supporting structures cannot be attached at internal nodes of substructures.

The data groups which define the beams, their alignment and their assembly into supporting structures are described below.

```

      *
      **
*****
      **
      *

```

## BEAms data group

Any number of lines each containing 9 items of data.

Used to define the characteristics of each beam which will be used to generate the supporting structures.

## Item

1	$n_B$	Beam number. (Positive integer, $\leq 120$ . Must not duplicate a beam or beam substructure number used elsewhere in data.)
2	EA	Axial stiffness.
3	EI	Flexural rigidity.
4	$P_L$	Live load (compression positive).
5	$P_D$	Dead load (compression positive).
6	L	Length of beam.
7	m	Mass per unit length.
8	$\nu$	Poisson's ratio.
9	SF	Shape factor.

The axial load in the beam in a buckling problem is  $P_D + FP_L$ , where F is the load factor for which the program finds the value when buckling occurs. In a vibration problem the axial load is  $P_D$ , and  $P_L$  may be set to zero (or given a dummy value). m is vital in all design problems and in vibration analysis problems.  $\nu$  and SF are only needed when shear deflection is allowed for (see LS in the RESet data group, page 99). If  $\nu$  is omitted, the value zero is used. If SF is omitted, the global value from the RESet data group is used (see page 100).

\*\*\*\*\*  
 \*  
 \*  
 \*  
 \*  
 \*

## BALignment data group

Consisting of rotation, offset, beam substructure and cylindrical axes data. Any number of lines, with text on some.

This data group is used to specify alignment transformations for beams and beam substructures, prior to their assembly into supporting structures. Four separate types of data instructions are included: (1) rotation of beams or beam substructures; (2) offsets of the ends of beams or beam substructures; (3) linking together of beams or beam substructures to form new beam substructures; and (4) defining beams or beam substructures in terms of cylindrical axes. These instructions are identical to those used for plates and substructures in the ALignment data group, and are summarized below. For further information, please refer to the fuller descriptions given above for the Alignment group (see pages 53-60) and to Appendix 2 (see pages 152-163).

Rotation (part of BALignment data)

† R  $b_n$   $b_o$   $\mu$

## Item

- |   |       |  |
|---|-------|--|
| 1 | R     | Type Rotate (or just R) to indicate a beam is to be rotated.   |
| 2 | $b_n$ | Reference number of new, i.e. rotated, beam or beam substructure. Must not duplicate a beam or beam substructure number used elsewhere in data.  |
| 3 | $b_o$ | Reference number of old, previously defined, beam or beam substructure which is rotated to give $b_n$ . $b_o$ and $b_n$ must be both doubly connected ( $\leq 120$ ) or both singly connected ( $> 120$ ). |

- 4       $\mu$       Anti-clockwise angle of rotation in degrees between y axis and a straight line originating at end 1 and connecting to end 2, see figure 5.3(b).

Offset (part of BALignment data)

†      0  $b_n$   $b_o$   $e_{y1}$   $e_{z1}$   $e_{y2}$   $e_{z2}$

Item

- |     |  |   |
|-----|--|---|
| 1   | 0  | Type Off (or just 0) to indicate this is an offset.   |
| 2   | $b_n$  | Reference number of new beam or beam substructure, i.e. after offsets added. Must not duplicate a beam or beam substructure number used elsewhere in data.  |
| 3   | $b_o$  | Reference number of old, previously defined, beam or beam substructure to which offsets are added to give $b_n$ . $b_o$ and $b_n$ must be both doubly connected ( $\leq 120$ ) or both singly connected ( $> 120$ ).  |
| 4-7 | $e_{y1}$<br>$e_{z1}$<br>$e_{y2}$<br>$e_{z2}$ | The offsets (i.e. eccentric connections) in the y and z directions, at ends 1 and 2 respectively, of a beam or doubly connected beam substructure, with the positive direction taken from the end of the beam to the node, see figure 5.3(c). Similarly $e_{y1}$ and $e_{z1}$ are the offsets of the connection node of a singly connected beam substructure. |

Beam Substructure (part of BALignment data)

†       $b_n b_o \dots$

## Item

- 1       $b_n$       Beam substructure number.      Positive integer  $\leq 899$ . If  $\leq 120$ , doubly connected; if  $\geq 121$ , singly connected. Must not duplicate a beam or beam substructure number used elsewhere in data.

set i      Given in the order set 1, set 2, ..., set  $N_{sub}$ . Set i relates to node i of the chain of nodes forming the beam substructure (see page 152).

## Item for set i

- 1       $b_o$       Reference number ( $\leq 120$ ) of any previously defined beam or doubly connected beam substructure connecting node i to node i + 1. End 1 of the beam or beam substructure must be at node i.
- 2       $-b_{o1}$       If other previously defined beams or doubly connected beam substructures also connect nodes i and i + 1, their reference numbers are given with reversed sign (i.e. negative integers  $\geq -120$ ).
- or       $b_{o2}$       If any previously defined singly connected beam substructures are connected to node i, their reference numbers ( $> 120$ ) are given.
- or       $900+n_s$       If there is a point support at node i of the beam substructure, the integer given here is 900 plus its reference number in the LONGitudinal line supports data (see page 65). Thus the integer 903 indicates the presence of the support defined by the third line in the LONGitudinal line supports input.

3,4,... As item 2, with items continuing to be given (in any order) until all data relating to node  $i$  has been given.

When node  $N_{\text{sub}}$  has singly connected beam substructures and/or point supports connected to it, enter 0 (i.e. zero) as item 1, then the appropriate values for items 2, 3, etc.

Cylindrical coordinate transformation (part of  
BALignment data)

†       $C \ b_n \ b_o \ \mu$

Item

- |   |       |   |
|---|-------|---|
| 1 | $C$   | Type Cyl (or just C) to indicate this is a cylindrical coordinate transformation.   |
| 2 | $b_n$ | Reference number of new beam or beam substructure, i.e. after cylindrical coordinate transformation. Must not duplicate a beam or beam substructure number used elsewhere in data.                          |
| 3 | $b_o$ | Reference number of old, previously defined, beam or beam substructure which is transformed into $b_n$ . $b_o$ and $b_n$ must be both doubly connected ( $\leq 120$ ) or both singly connected ( $> 120$ ). |
| 4 | $\mu$ | Clockwise angle of rotation of yz axes at end 1 in degrees. The yz axes at end 2 undergo the opposite rotation.   |

```

      *
      **
*****
      **
      *

```

## SUPporting structures data group

Any number of sets of 2, 3, 4 or more lines.

This data group defines the assembly of beams and beam substructures into supporting structures and the attachments of the supporting structures to the plate assembly. Each set of data defines one supporting structure, and contains data of up to 4 types (of which either the first or the second, and also the fourth, may be omitted), and which must appear in the following order.

Item, of type 1 data (1 line, containing text plus 1 or more triplets of data)

1        C        Type Connection (or just C) to denote the connection list.

2-4,...        Triplets defining the connection list of the supporting structure in the usual style (see page 62), i.e. (1) lower numbered node; (2) higher numbered node; (3) beam or doubly connected beam substructure reference number, as given in the BEAMs or BALignment data (see pages 69 and 72). Each node in the final supporting structure must coincide with a panel node and have the same node number. The % continuation feature may be used if the list requires more than one line.

Item, of type 2 data (1 line, containing text plus 1 or more doublets of data)

1        A        Type Attachment (or just A) to denote the attachment list.

2-3,...        Doublets defining the attachment list of the supporting structure in the usual style (see page 63), i.e. (1) node number; (2) singly connected beam substructure reference number, as given in the BALignment data (see page 72), or 900 + reference number of an entry in the LONGitudinal line supports data which gives supports to be attached to this node of the supporting structure (see page 65). (These are interpreted as point supports rather than the usual line supports, and should not affect the out-of-plane freedom u.) Each node in the final supporting structure must coincide with a panel node and have the same node number. The % continuation feature may be used if the list requires more than one line.

Item, of type 3 data (1 or more lines, each containing 1 or more items of data)

This data defines attachments of degrees of freedom at nodes of the supporting structure to those of the panel. If different combinations of degrees of freedom are to be attached at different nodes, one line of type 3 data should be entered for each combination.

1        A three digit integer giving the degrees of freedom of the supporting structure to be attached to the corresponding freedoms of the panel (2=v, 3=w, 4=ψ).

2,...      A list of node numbers at which this combination of attachments of supporting structure and panel freedoms applies. All the node numbers must have appeared above in either the type 1 or the type 2 data. If no node numbers are given, the attachments are made at all remaining nodes whose attachments have not already been defined in the type 3 data. (This makes the data very concise in the common situation where the same degrees of freedom are attached at all nodes: this requires 1 line of type 3 data containing only item 1, i.e. no node numbers need be given.)

Item, of type 4 data (1 line, containing text plus 1 or more items of data)

1      X      Type X (or X =).

2,...      List of values of x at which the supporting structure occurs. (This line may be omitted when only x = 0 is wanted.)

### 5.8 Repetitive Plate Assemblies

This section covers the following data groups:

REPetitive plates, beams and substructures  
TRANsverse wavelength

This section describes the additional data input which is required when modelling repetitive cross-sections in the manner described in section 3.4 (see pages 14-19). It is only necessary to define one repeating portion of a repetitive plate assembly. The repeating portion is modelled in exactly the same way as for a regular plate assembly except for the following modification. Plates, substructures, beams and beam substructures which connect the datum repeating portion to an adjacent portion, such as the plates connecting node 1 to node (3) and node 2 to node (4) on figure 3.3(a), must be identified in the REPetitive data group, which is described below. The analysis is made for the infinitely wide plate assembly by assuming that the mode repeats over certain transverse wavelengths, as specified in the TRANsverse wavelength data group described at the end of this section.

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REPetitive plates, beams and substructures  
data group

One or two lines, each with any amount of  
data.

This data group lists the reference numbers of all plates, substructures, beams and beam substructures which connect from the datum repeating portion to an adjacent one. The usual rules for having the proper orientation for these plates, beams or substructures must be followed, together with the rule that edge 1 must correspond to the lower numbered node of the connection and be in the datum repeating portion. Triplets of integer data defining the connection must be given in the CONNecTion data (see page 62) or the SUPPorting structures type 1 data (see page 74) in the usual way. Connections from a node in the datum

repeating portion to the counterpart of the same node in an adjacent repeating portion are permitted.

#### Plates and substructures

† P P<sub>1</sub> P<sub>2</sub> ...

##### Item

- |       |                |  |
|-------|----------------|--|
| 1     | P              | Type P (indicating repetitive plates).   |
| 2,... | P <sub>1</sub> | List of integers, of which each absolute value gives the reference number of a plate or substructure which connects from the datum repeating portion to an adjacent one. Enter positive for a connection to the next repeating portion, negative for a connection to the previous repeating portion. |

#### Beams and beam substructures

† B b<sub>1</sub> b<sub>2</sub> ...

##### Item

- |       |                |  |
|-------|----------------|--|
| 1     | B              | Type B (indicating repetitive beams).  |
| 2,... | b <sub>1</sub> | List of integers, of which each absolute value gives the reference number of a beam or beam substructure which connects from the datum repeating portion to an adjacent one. Enter positive for a connection to the next repeating portion, negative for a connection to the previous repeating portion. |

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### TRANsverse wavelength data group

Any number of lines each containing any number of triplets of data, of the form

$v_1 \quad v_2 \quad v_{inc}$

The program determines the transverse half-wavelengths  $\lambda_T$  to be considered from the values given in both the TRANsverse wavelength data and the WIDTH data (see page 39).

If no TRANsverse wavelength data is entered, the program automatically selects appropriate transverse half-wavelengths as follows. If  $P$  in the WIDTH data is finite, values of  $g$  in the range  $-P < g \leq P$  will be used where the absolute value of  $g$  is the number of half-wavelengths in the response over a width of  $P$  transverse bays. To cover the complete range for an infinitely wide plate assembly (i.e. if  $P$  was entered as zero or if the WIDTH data was omitted), a parameter  $\eta$  is varied from  $-1$  to  $1$ . Calculations are made at INTP equally spaced intervals in the range from  $0$  to  $1$ , where INTP is a RESet variable (see page 97). Calculations are only made in the negative range of  $g$  or  $\eta$  where the results would be different from those obtained for the positive values, as discussed in section 3.4 (see page 16).

If the default list of values of  $g$  or  $\eta$  indicated above is not required, the user may construct a list of values using the TRANsverse wavelength data, as follows.

The data consists of triplets of values: these are values of  $g$  if  $P$  is finite and values of  $\eta$  if  $P$  is infinite. For each triplet,  $g$  or  $\eta$  takes the initial value  $v_1$  and is incremented by  $v_{inc}$  until the limit  $v_2$  is passed. Only positive values of  $g$  or  $\eta$  should be generated in this way, because calculations will be performed automatically for the corresponding negative values when required (see section 3.4, page 16).

### 5.9 Optimum Design

The input controlling the execution of the design process is described under headings DESign, STAbilize on and STAbilize OFF in section 5.1 (see page 34) and also includes a number of RESet variables (see CMASS, CSTAB, FACBND, KKKMAX, SMOVE and PSMOVE on pages 96, 98 and 100). The following data groups are used for the additional input required for the design application of the program described in chapter 4 (see pages 22-27). This input must be used in conjunction with all the relevant sections of input described elsewhere so that analysis of the problem at the various stages of design is correct.

Note that DESign problems (or ANALysis problems for which sensitivities are required) can only be solved with respect to BUCkling analysis.

For DESign problems (and ANALysis problems with sensitivities) the user is required to supply data to indicate which parameters are design (independent) variables, by means of the SENSitivities data group. The effects of changing the values of design variables on other quantities (i.e. dependent variables) should also be specified, using the LINKing and ANGLE definition data groups. For DESign problems the upper and lower limits on the value of design variables may be entered using the BOUNDS data group, and inequality constraints may be entered within the LINKing data group. For ANALysis problems in which the SENSitivities data group is used, the sensitivities of each eigenvalue with respect to each 'design variable' will be calculated and printed following the analysis.

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### SENSitivities data group

Up to three lines each containing at least two items of data.

This data group gives the reference numbers of the plate breadths, layer thickness and layer ply angles which are design variables in a DESIGN problem (or for which sensitivities are required in an ANALYSIS problem). One line of each of the following types is permitted.

#### Breadths of plates (part of SENSitivities data)

†      B n<sub>p1</sub> n<sub>p2</sub> ...

Item

- |                        |   |  |
|------------------------|---|--|
| 1                      | B | Type Breadth (or just B) to indicate plate breadths.   |
| 2, ... n <sub>pi</sub> |   | Reference number of a plate (i.e. the number given as item 1 in the PLATE data, see page 49) whose breadth is a design variable. |

#### Thicknesses of layers (part of SENSitivities data)

†      T n<sub>L1</sub> n<sub>L2</sub> ...

Item

- |                        |   |  |
|------------------------|---|--|
| 1                      | T | Type Thickness (or just T) to indicate layer thicknesses.  |
| 2, ... n <sub>Li</sub> |   | Reference number of a layer (i.e. the number given as item 1 in the LAYER data, see page 44) whose thickness is a design variable. |

Ply angles of layers (part of SENSitivities data)

$$+ \quad A \quad n_{L1} \quad n_{L2} \quad \dots$$

Item

1        A        Type Angle (or just A) to indicate layer ply angles.

2,... n<sub>Li</sub> Reference number of a layer (i.e. the number given as item 1 in the LAYER data, see page 44) whose ply angle is a design variable.

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      *
    * *
  * * * * *
    * *
      *

```

LINKing data group

Any number of lines each constituting a linking equality or inequality and containing at least 7 items of data.

This data group gives the linear equalities and inequalities which link dependent variables, design variables and constant values. Each line of data specifies the left hand side and right hand side of an equality or inequality described generally by equations 4.1 or 4.2 respectively. Note that parameters whose coefficient is zero need not be entered.

Equality linking defines the value of the dependent variables. Each line of data consists of the left hand side parameters,  $B_{Dik}X_{Dk}$ , followed by the right hand side parameters,  $B_{Iij}X_{Ij}$  and  $B_{F1l}X_{F1l}$ , followed by the  $C_i$ , of equation 4.1. A consistent input must have as many unique equations as there are dependent variables (i.e.  $n_D$  unique equations).

Inequality linking specifies limits on the values of design variables and dependent variables in terms of other design variables, dependent variables and constant values. The format is more general than can be specified by upper and lower bounds on design variables in the BOUNDS data group (see pages 87-88).

These inequalities have the same effect as other design constraints (e.g. buckling constraints). Each line of data consists of the left hand side parameters,  $B_{Lij}X_j$ , followed by the right hand side parameters,  $B_{rij}X_j$ , followed by the  $C_i$ , of equation 4.2. The format is the same as for equality linking except in this case, any combination of dependent variables, design variables or fixed parameters may occur on either side of the inequality.

Four separate types of parameter may be included in the LINKing group: plate breadths, layer thicknesses, layer ply angles and offsets of the ends of plates or substructures. (ANGLE definition, which defines angles of rotation or cylindrical coordinate transformation of plates and substructures in terms of design variables, dependent variables or constant values, is described below, see pages 85-87.)

Each parameter is defined by a triplet of data. The first item of each triplet is the value of the coefficient of the parameter referenced by the second and third items. The second item of the triplet is a character string which describes the parameter type (B for Breadth, T for layer Thickness, A for layer ply Angle, O for Offset followed by Y or Z for offset direction and 1 or 2 for the edge of the plate or substructure to be offset, e.g. OY1 describes the offset in the Y direction of edge 1). The third item of the triplet is the reference number the parameter has in the PLate (for breadths, see page 49), LAYer (for layer thicknesses and layer ply angles, see page 44) or ALIgnment (for plate or substructure offsets, see page 56) data. The % continuation feature may be used if the data requires more than one line.

#### Item

1,2,...,n	Triplets of data describing the parameters on the left hand side of the equality or inequality (see equations 4.1 and 4.2 respectively).
-----------	--

- n+1    E or G    Type E to indicate an equality and the position of the Equals sign separating the left hand side from the right hand side. Type G or L to indicate an inequality and the position of the Greater than or equal to or the Less than or equal to sign separating the left hand side from the right hand side.
- n+2,n+3,...,m    Triplets of data describing the parameters on the right hand side of the equality or inequality (see equations 4.1 and 4.2 respectively).
- m+1                Value of the constant term on the right hand side of the linking equality or inequality. If this value is zero it need not be entered.

For example (denoting the thickness of layer  $i$  by  $T(i)$ ), suppose that  $T(1)$  and  $T(2)$  are independent variables, the value of  $T(3)$  is held fixed, the offsets OZ1 and OZ2 of substructure 12 are dependent on  $T(1)$ ,  $T(2)$  and  $T(3)$ , and the values of  $T(1)$  and  $T(2)$  are constrained by an inequality in the following way.

$$\begin{aligned} \text{OZ1}(12) &= 2 T(1) + 3 T(2) + T(3) + 0.125 \\ \text{OZ2}(12) &= 2 T(1) + 3 T(2) + T(3) + 0.125 \\ 2 T(1) &\geq 3 T(2) + 0.25 \end{aligned}$$

These conditions are specified by the following LINKing data.

```
LIN
1.0 OZ1 12 E 2.0 T 1 3.0 T 2 1.0 T 3 0.125
1.0 OZ2 12 -1.0 OZ1 12 E 0.0
2.0 T 1 G 3.0 T 2 0.25
```

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 \*

### ANGLE definition data group

Any number of lines each containing 5 items of data.

In a DESIGN problem (or an ANALYSIS problem involving SENSitivity calculations), certain configurations involve plate elements having angular orientations which vary with the design variables. The conventional way (see pages 54 and 59) of defining such an angle would not be suitable, but the angle can be defined in terms of an inverse trigonometric function. The means of specifying these angles is given in this data group by defining the angles of plate or substructure rotations and cylindrical coordinate transformations in terms of plate breadths and constant values. The breadths may be dependent variables, design variables or held fixed. The user may also wish to use variable plate projections which are not used as plate breadths in the problem, in which case a dummy plate may be used whose breadth is a design variable or a dependent variable defined by a LINKing equation (see pages 82-84).

Although the principal use of the ANGLE definition group is to define angles which vary with the design variables, it may also be used in any ANALYSIS or DESIGN problem to define fixed angles in terms of their sines, cosines or tangents. For instance, in example 6.5 (see pages 136-139), a plate is rotated by  $\cos^{-1}(0.75)$  without the user having to evaluate this angle in degrees.

#### Item

- |   |                |   |
|---|----------------|---|
| 1 | P <sub>n</sub> | Reference number of the plate or substructure which has been newly defined by a Rotation or Cylindrical transformation in the ALIGNment data (see pages 54 and 59). The angle of rotation or cylindrical coordinate transformation is defined in terms of a basic angle, $\theta_0$ , lying between 0° and 90° using the following three items of data, while the |
|---|----------------|---|

fourth item gives the quadrant in which the angle lies.

- 2      S or C or T      Defines whether the quotient given by the following two items of data defines the absolute value of the Sine (S), Cosine (C) or Tangent (T) of  $\mu_0$ .
- 3       $p_1$  or  $Vp_1$       The positive numerator of the quotient which defines  $\mu_0$ . If input as a number  $p_1$  only, then  $p_1$  is the reference number of a plate whose breadth is the numerator. If input as  $Vp_1$  then the V indicates that the positive number  $p_1$  is the Value of the numerator.
- 4       $p_2$  or  $Vp_2$       The positive denominator of the quotient which defines  $\mu_0$ . If input as a number  $p_2$  only, then  $p_2$  is the reference number of a plate whose breadth is the denominator. If input as  $Vp_2$  then the V indicates that the positive number  $p_2$  is the Value of the denominator.
- 5       $p_q$       A single integer of value 1, 2, 3 or 4 defining in which quadrant the angle of rotation or cylindrical transformation lies, the basic angle  $\mu_0$  (lying between  $0^\circ$  and  $90^\circ$ ) having been defined by the previous three items.

$p_q$	Angle of rotation or cylindrical transformation
1	$\mu_0$
2	$180^\circ - \mu_0$
3	$180^\circ + \mu_0$
4	$-\mu_0$

For example, suppose that plate 1 is rotated (nominally) by  $-45^\circ$  in the ALIGNment data to give a newly defined plate 2, the breadth of plate 1 is a design variable and the projection of plate 2 on the y axis is to be held fixed at the value 0.5. The ANGLE definition data for this plate would be as follows.

ANG  
2 C V0.5 1 4

Note that it would be desirable to include the LINKing inequality (see pages 82-84)

LIN  
1.0 B 1 G 0.5

in order to prevent the arccosine from being undefined.

```

      *
      **
***** **  BOUNds on design variables data group
      **
      *

```

Up to six lines each containing at least three items of data.

This data group specifies constant values as the upper and lower bounds on the design variables. The default values of bounds for breadths and layer thicknesses of  $1.0 \times 10^{10}$  (upper) and 0.0 (lower) and for layer ply angles of  $1.0 \times 10^{10}$  (upper) and  $-1.0 \times 10^{10}$  (lower) are used if no user supplied bounds are given.

† Bounds on design variable plate breadths (part of BOUNds data)

Item

1 BU or Type B and then U or L to indicate that the  
BL following items represent upper or lower  
bounds.

2,3,... Doublets of data, the first item being the reference number of the design variable plate breadth (i.e. the number  $n_p$  given as item 1 in the PLate data, see page 49) whose bound is given by the second item.

† Bounds on design variable layer thicknesses (part of BOUnds data)

Item

- 1      TU or      Type T and then U or L to indicate that the  
          TL      following items represent upper or lower  
               bounds.
- 2,3,...      Doublets of data, the first item being the  
               reference number of the design variable layer  
               thickness (i.e. the number  $n_L$  given as item 1  
               in the LAYer data, see page 44) whose bound  
               is given by the second item.

† Bounds on design variable layer ply angles (part of BOUnds data)

Item

- 1      AU or      Type A and then U or L to indicate that the  
          AL      following items represent upper or lower  
               bounds.
- 2,3,...      Doublets of data, the first item being the  
               reference number of the design variable layer  
               ply angle (i.e. the number  $n_L$  given as item 1  
               in the LAYer data, see page 44) whose bound  
               is given by the second item.

## 5.10 Plotting

This section covers the following data groups:

PLOt  
CROss-sectional plotting  
NODEs

The data groups described in this section are used to obtain plots of the undeformed structure and of modes from the eigenvalue analysis. In design problems, where many intermediate configurations may be analyzed, plotting is restricted to the undeformed plots of the original and final designs, together with the specified mode plots for the final design.

The entire cross-section of the undeformed plate assembly may be plotted. More detailed cross-sections of selected plates and substructures, showing the individual layer thicknesses, may also be specified.

Mode shapes may be found and plotted at all eigenvalues, or at a selection of the lowest eigenvalues (see the PFAST data on page 40). For the VIPASA analysis, cross-sectional mode shapes of the entire plate assembly are made. If all plates are orthotropic and carry no shear load, one mode is plotted. Otherwise two modes which are at longitudinal (x) locations  $\lambda/2$  apart are plotted (corresponding to the real and imaginary modes of the complex formulation of VIPASA, see ref. 3). For the VICON analysis, mode shapes are plotted at the values of x given by the XLOCATION data (see page 36), and contour and isometric plots may be made of the deflected shape for any group of nodes such as those on the skin of a panel, as specified in the NODEs data (see page 93).

For either VIPASA or VICON analysis, plots may be made of the perturbation stress levels within laminated plates (i.e. the stresses caused by the deformation of the plate assembly into its mode shape). The NODEs data (see page 93) is used to specify the part of the plate assembly in which stresses are to be calculated, and each pair of adjacent nodes given there must be connected by a single plate (or doubly connected substructure, see pages 57-59) with the same layup. The program generates a grid of (x,y) values at which to

calculate stress levels, the number of grid points being controlled by NUMX and NUMY in the RESet data (see page 99). At each grid point, the three in-plane stresses are calculated at the mid-surface of each layer, either in material coordinates as  $\sigma_1$ ,  $\sigma_2$  and  $\tau_{12}$  or in plate coordinates as  $\sigma_x$ ,  $\sigma_y$  and  $\tau_{xy}$ , and the two inter-laminar shear stresses  $\tau_{xz}$  and  $\tau_{yz}$  are calculated (in plate coordinates) at the boundaries between layers. (Material coordinates are used by default for the in-plane stresses, but plate coordinates may be selected by setting ISPC = 1 in the RESet data, see page 98.) For each of the five stresses calculated, a contour plot may be made at the layer or boundary where the maximum stress occurs, or at every layer or boundary, and a section plot showing the variation of stress through the thickness of the plate may be made at the grid point where the maximum stress occurs, or at every grid point. Normally the mode shape calculations give the deflections only at the edges of each plate and the values at points within the plate are found by interpolation. However, internal deflections can often be obtained more accurately by specifying an automatic subdivision of the plate (for the mode and stress calculations only) into a number of identical smaller plates, by means of item 6 of the PLate data (see page 49).

If eigenvalues are found for several values of the wavelength ( $\lambda$  or  $\epsilon$ ) and transverse wavelength ( $g$  or  $\eta$ ) parameters, graphs may be plotted showing their variation with these parameters.

In addition to the PLOt, CROSS-sectional plotting and NODEs data groups described below, graphical output is also affected by the settings of the following RESet variables (see page 95): HORIZ, VERT, HT, INMOD, INTM, IPLSY, ISYM1, ISYM2, XSYM, ISPC, NC, NLEN, NUMX, NUMY and NWID.

```

      *
    ***
*****
      *

```

PLOt data group

One line with 5 items of data.

IPLLOT, ISCON, AMP, IGRAPH, ISTRS

If IPLLOT = 0 no plotting is done.

If IPLLOT  $\neq$  0, the undeformed structure is plotted together with any specified CROSS-sectional plots of plates and substructures (see page 92). Mode shapes are calculated and plotted, with the value of IPLLOT controlling the appearance of the cross-section mode plots as follows.

IPLLOT = 1 Undeformed structure and mode shapes plotted as solid lines.  
 = 2 Undeformed structure plotted as dashed lines, mode shapes as solid lines.  
 = 3 Mode shapes only plotted as solid lines.  
 = -n (n = 1, 2 or 3) As for IPLLOT = +n, except that the mode shapes are also printed in tabular form. (To obtain printed modes only, the user should set IPLLOT = 0 and use the MODEs data, see page 36.)

ISCON = 0 No isometric or contour plots are made.  
 = 1 Contour plots are made showing the w deflection.  
 = 2 An isometric view of the deflected shape is plotted.  
 = 3 Both contour and isometric plots are made.  
 (The NODEs data group, see page 93, is used to specify the surface over which the contour and isometric plots are made, while the number of grid points is controlled by NUMX and NUMY in the RESet data group, see page 99.)

AMP Controls the amplitude of the mode shape in the cross-section plots. Usually a value of the order of unity produces desired results. Default 1.

- IGRAPH = 0 No graphs are plotted.
- = 1 A graph is plotted of eigenvalue against  $\lambda$  or  $\epsilon$ . In repetitive analyses, this is repeated for each value of  $g$  or  $\eta$ .
- = 2 In repetitive analyses, a graph is plotted of eigenvalue against  $\eta$  for each value of  $\lambda$  or  $\epsilon$ .
- = 3 Both the above sets of graphs are plotted.
- ISTRS = 0 No perturbation stress levels are calculated or plotted.
- = 1 For each of the three in-plane stresses ( $\sigma_1$ ,  $\sigma_2$  and  $\tau_{12}$  or  $\sigma_x$ ,  $\sigma_y$  and  $\tau_{xy}$ , see page 90), and for each of the two inter-laminar shear stresses ( $\tau_{xz}$  and  $\tau_{yz}$ ), a contour plot is made at the layer or boundary where the maximum stress occurs.
- = 2 For each of the three in-plane stresses and for each of the two inter-laminar shear stresses, a section plot through the thickness of the plate is made at the (x,y) grid point where the maximum stress occurs.
- = 3 Both the above sets of plots are made.
- = -n (n = 1, 2 or 3) As for ISTRS = +n, except that the contour plots are made at every layer or boundary and the section plots are made at every grid point.

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 \*

#### CROss-sectional plotting data group

One line containing any number of items of data.

Each item is an integer giving the reference number of a plate or substructure for which a detailed cross-section plot, showing the layups used in each plate, is required. The value zero will generate such a plot of the whole plate assembly.

```

      *
      *
***** *
      *
      *

```

NODes data group

One line with any amount of data.

Contour and/or isometric plots of the  $w$  displacement, and/or plots of the perturbation stress levels, can be made for any surface by listing the nodes to be included in the surface in the NODes data group. For example all the nodes of the skin of a panel, omitting any on stiffeners, could be listed. The sequence is such that, when the surface is seen in cross-section, nodes which are physically adjacent are listed in order. Default is all the nodes in numerical order.

In order to generate the plots, the program calculates the displacements or stress levels at each of a set of grid points in the  $(x,y)$  plane. The number of grid points is controlled by NUMX and NUMY in the RESet data group (see page 99).

For the contour and isometric plots of the  $w$  displacement, horizontal ( $y$ ) projections are used for each connection between adjacent nodes, so that some plates may appear shortened if the skin is not flat. If cylindrical coordinates are used, each connection between adjacent nodes is rotated back by the amount of the axis rotation to achieve the effect of unwrapping a cylindrical surface onto a plane.

For the stress level plots, the CONNecTion between each pair of adjacent nodes must be a single plate or a doubly connected substructure comprising plates which are joined together to form a chain.

WARNING: These connections must not appear out of sequence in the CONNecTion data. (see page 62).

All the PLates forming the surface must be formed from laminated WALLs with the same layup. For the stress level contour plots, the program uses the actual distance between adjacent nodes rather than the horizontal ( $y$ ) projection, to achieve the effect of unwrapping the surface onto a plane.

### 5.11 Reset Capability

This section covers the following data group:

#### RESet

Several variables are seldom changed for different problems and take the default values assigned in the program. Different values can be given to these variables by using the RESet data group. The variables which may be input through the RESet capability are listed below along with their default values. Users may wish to alter the source code (SUBROUTINE INIT) to change the default values to others that are more commonly encountered. Unlike other groups, the RESet data group can appear more than once at arbitrary locations in the input. Care should be taken that subsequent data input does not overwrite a desired RESet value.

RESet data may be used in the specification of a CHAnge set (see section 5.13, page 104). However, some of the RESet variables are regarded as global to the problem and may not be assigned a new value in a change set. The global variables are identified in the descriptions below.

```

      *
      *
*****
      *

```

## RESet data group

Special line(s) of data to change certain variables from their default values.

VARIABLE	DEFAULT
CMASS (global)	.01
CSTAB (global)	.001
FACBND (global)	1.15
HORIZ (global)	site dependent
VERT (global)	site dependent
HT (global)	site dependent
IDBUG	5
IDEFF	1
INMOD	0
INTM	10
INTP	6
IPLSY	1
ISYM1	1
ISYM2	highest node number
XSYM	.5
ISPC	0
ITMAX (global)	8
KKKMAX (global)	3
LR	0
LS	0
NC	5
NEMAX	5
NIMAX	9999
NLEN	1
NUMX	50
NUMY	50
NWID	1
SF	.8333...
SMASPR	$1.*10^{-12}$
SMOVE (global)	.45 or .2 (see page 101)
PSMOVE (global)	.9 or .8 (see page 101)
TOLA	.01
TOLB	$1.*10^{-9}$
TOLG	.001
TOLM	.001

These variables are defined as follows.

- CMASS (global)** Convergence factor used in the mass difference convergence tests which form part of the criteria for the 'stop CONMIN cycling' and 'stop sizing cycling' shown in figure 4.1 and described on page 26. CONMIN cycle convergence occurs when the relative difference between the mass of the configurations following the CONMIN optimization step of two successive CONMIN cycles does not exceed CMASS. Sizing cycle convergence occurs when the relative difference between the lowest stabilized mass during the previous sizing cycle and the lowest stabilized mass during the current sizing cycle does not exceed  $2.0 * CMASS$ .
- CSTAB (global)** Convergence factor for the adjustment of all layer thicknesses that are design variables to achieve the 'just stable' condition during the stabilization steps of figure 4.1. Convergence occurs when the thickness factor required to bring the eigenvalue (buckling load factor) of the most critical mode to unity has been found to a relative accuracy of CSTAB.
- FACBND (global)** The upper bound on the buckling load factors for which the constraint and sensitivity analysis step of figure 4.1 is carried out. An active set of buckling constraints and sensitivities is calculated and updated for each sizing cycle. Buckling constraint and sensitivity calculations are avoided for buckling load factors which are greater than FACBND.

HORIZ (global) Horizontal and vertical sizes of plots.  
 VERT (global) Default values are set in the source code of the program at installation depending on the scale of the plotting device.

HT (global) Character height used by plotting device.

IDBUG Causes certain diagnostic printing as indicated in the beginning of the source code of the main program (VICONOPT).

IDEFF A value of 1 causes the effective [D] matrix (see Appendix 1, page 150) to be used for all layered plates. A value of 0 causes the regular [D] matrix to be used which will be different from [D]<sub>eff</sub> if the [B] matrix is not zero.

INMOD A value of 1 causes mode shapes to be calculated accurately at the internal points of all substructures instead of simply at the nodes of the final structure. Thus the cross-sectional mode plots give a more accurate representation of the deflected shape of the structure.

INTM Number of interior points within each plate or substructure for which the cross-section mode shape is estimated and plotted. The interior shape is interpolated from end point displacements and rotations and is not exact.

INTP Number of values of transverse half-wavelengths  $\lambda_T$  calculated for an infinitely wide panel using the repetitive analysis, see pages 17 and 79.

IPLSY  
 ISYM1  
 ISYM2  
 XSYM

These variables are used to specify the calculation of modes which are point symmetric or point antisymmetric. This may be achieved for a VICON analysis with  $0 < \epsilon < 1$  whenever the plate assembly, including its supports and loading, is point symmetric about an axis which is parallel to the z axis. If IPLSY = 0 no point symmetry or antisymmetry is sought. If IPLSY = 1 the program will find a mode which is point symmetric about this axis, while if IPLSY = -1 a point antisymmetric mode will be found. ISYM1 and ISYM2 must be set to the numbers of any two nodes which are symmetrically placed about the longitudinal plane of symmetry which contains the axis of point symmetry. XSYM specifies the longitudinal position of the axis of point symmetry as  $x = XSYM * \epsilon$ . Note that if the structure is not point symmetric, or if ISYM1 and ISYM2 have inappropriate values, the program finds a valid mode shape but this exhibits no point symmetry or antisymmetry.

ISPC

A value of 1 causes the in-plane perturbation stress levels (see page 90) to be calculated in plate coordinates as  $\sigma_x$ ,  $\sigma_y$  and  $\tau_{xy}$ . A value of 0 causes them to be calculated in material coordinates as  $\sigma_1$ ,  $\sigma_2$  and  $\tau_{12}$ .

ITMAX (global) Maximum number of optimization iterations permitted during each call to CONMIN.

KKKMAX (global) Maximum number of CONMIN cycles permitted in each sizing cycle. When stabilization is not performed there is only one CONMIN cycle in each sizing cycle.

LR

A value of 1 allows for rotatory inertia in the beam stiffness calculations.

- LS                    A value of 1 allows for shear deflection in the beam stiffness calculations.
- NC                    In the contour plots (see page 89), contour lines are drawn at evenly spaced intervals of displacement or stress. The number of contour lines between zero and the maximum absolute value of displacement or stress is NC.
- NEMAX                Maximum number of distinct eigenvalues that will be calculated at each value of  $\lambda$  or  $\epsilon$  (or each combination of values of  $\lambda$  or  $\epsilon$  and  $g$  or  $\eta$  for a repetitive analysis) when all eigenvalues in the range  $F_L$  to  $F_U$  in the TRIal values data are requested (see page 35). If this maximum is reached, the program proceeds to the next value (or combination).
- NIMAX                The absolute value of NIMAX gives the maximum number of iterations allowed when converging on an eigenvalue. If this maximum is reached, the program proceeds to find the next eigenvalue. If NIMAX is negative, the program prints the CPU time for each iteration.
- NLEN                Length of structure shown in the contour, isometric and stress level plots (see pages 89-90) is  $NLEN * \ell$ , starting at  $x = 0$ . ( $\ell$  is the panel LENGTH, see page 37.)
- NUMX  
NUMY                Number of grid points in the  $x$  and  $y$  directions used to generate contour, isometric and stress level plots (see pages 89-90).

**NWID** In a repetitive problem, plots and mode shape calculations are made over NWID transverse bays of the structure. Note that NWID affects only the presentation of results, operating independently of the value of P given in the WIDTH data (see page 39) which defines a physical characteristic of the structure.

**SF** Global value of shape factor for beam stiffness calculations.

**SMASPR** In a VICON analysis, rigid body freedoms are removed by adding a small elastic support to the translational degrees of freedom of each beam, and also to the translational degrees of freedom of each plate for the infinite wavelength calculations required when  $\epsilon = 0$  and  $m = 0$  (see page 13). The stiffness of each elastic support is SMASPR multiplied by the absolute value of the diagonal term of the beam or plate stiffness matrix to which it is to be added. If the resulting diagonal term has absolute value less than SMASPR it is increased to +SMASPR. The user is advised to check that the addition of these supports has a negligible effect on the eigenvalues found, particularly when using devices such as artificially high values of EA in order to ignore the axial behaviour of a beam.

**SMOVE (global)** These variables govern the move limits placed  
**PSMOVE (global)** on design variables before the CONMIN optimization step of figure 4.1. The move limits are given by

$$[X_{IU}] = [X_I^*] * (1.0 + \text{FSMOVE} * \text{SMOVE})$$

$$[X_{IL}] = [X_I^*] * (1.0 - \text{FSMOVE} * \text{SMOVE})$$

where  $[X_{IU}]$  and  $[X_{IL}]$  represent the upper and lower move limits imposed on  $[X_I]$ , the vector of design variables, and  $[X_I^*]$  gives the values of  $[X_I]$  at the start of the current sizing cycle. SMOVE is the prescribed sizing cycle move limit factor and remains fixed. FSMOVE is the CONMIN cycle move limit factor and takes the value  $(PSMOVE)^{n-1}$  for the first CONMIN cycle of the  $n^{\text{th}}$  sizing cycle. When stabilization is used, CONMIN cycling automatically adjusts FSMOVE for the second and subsequent CONMIN cycles of each sizing cycle. When no stabilization is performed, there is only one CONMIN cycle in each sizing cycle and so there is no automatic adjustment to FSMOVE.

NOTE. When stabilization is performed, SMOVE and FSMOVE have default values 0.45 and 0.9 respectively, but when no stabilization is performed the default values are 0.2 and 0.8 respectively.

## TOLA

The theory assumes that all plates are balanced, i.e. that the  $[A]$  matrix has  $A_{13} = A_{23} = 0$ . If a particular layup results in the absolute value of  $A_{13}$  or  $A_{23}$  exceeding  $TOLA * \max(A_{11}, A_{22}, A_{33})$  then a warning message is printed.

## TOLB

The theory assumes that all plates are symmetric, or that the  $[B]$  matrix can be eliminated using IDEFF = 1 (see page 97). If a particular layup results in the absolute value of any element of the  $[B]$  matrix exceeding  $TOLB * \sqrt{\{\max(A_{11}, A_{22}, A_{33}) * \max(D_{11}, D_{22}, D_{33})\}}$  then a warning message is printed.

- TOLG**            Tolerance for geometry compatibility which causes the program to stop when errors exceed  $\text{TOLG} * b_{\text{max}}$ , where  $b_{\text{max}}$  is the largest PLate breadth. Warning messages are printed when errors exceed  $.02 * \text{TOLG} * b_{\text{max}}$ .
- TOLM**            Additional tolerance on eigenvalue beyond that given by the ACCuracy data (see page 35) when mode shapes or sensitivities are requested (i.e. when MODE, PLOt or SENSitivities data is present, see pages 36, 91 and 81).

The value of any of these variables may be changed with the RESet data input. For example, HT and NIMAX can be changed as follows:

RESET

HT = 2.5   NIMAX=13

The = sign may be omitted if desired and data may appear on several lines.

## 5.12 Automatic Data Generation

Additional lines of data may be generated from any input line by using the following format. If the items on an input line are  $x_1, x_2, x_3, \dots$ , then the sequence of lines

```

x1      x2      x3 ...
= ( $\Delta_1 x_1$ ) ( $\Delta_1 x_2$ ) ( $\Delta_1 x_3$ ) ...
= ( $\Delta_2 x_1$ ) ( $\Delta_2 x_2$ ) ( $\Delta_2 x_3$ ) ...
.....
= ( $\Delta_m x_1$ ) ( $\Delta_m x_2$ ) ( $\Delta_m x_3$ ) ...
== (n1)
== (n2)
.....
== (nm)

```

produces  $n_1 \times n_2 \times \dots \times n_m$  lines. First the values of  $x_i$  are given and then incremented  $n_1 - 1$  times by  $\Delta_1 x_i$ . All of these lines are incremented  $n_2 - 1$  times by  $\Delta_2 x_i$  and so on. Several examples of the use of this input are given in chapter 6 (e.g. see pages 114 and 140-147).

### 5.13 Change Sets

The Change Set facility of VICONOPT allows different versions of the same problem to be run consecutively with very concise additions to the data of the original problem. An important application is to analyze or design a plate assembly allowing for a number of load cases, but the facility has been implemented in such a way that almost any of the problem data can be allowed to change, especially in analysis problems.

The data for the original problem is entered in the usual way. This problem is referred to as "Change Set 0", and this wording appears in the printed output even if multiple change sets are not being used.

If further change sets are to be entered, the original problem data must not be terminated by END. Instead, each subsequent change set is introduced by a CHAnge set line, which is described in section 5.1 (see page 41). Each change set is regarded as a modification of the original problem (change set 0), and the data for it which follows consists of entire data groups in their usual format. The following rules govern the preparation of data for a change set.

- (1) Any group which is identical to the corresponding group in change set 0 may be omitted.
- (2) Any group which is required in the current change set but which was absent in change set 0 is entered in the usual way.
- (3) Any group which contains changes (additions, deletions or modifications) to the corresponding group in change set 0 is entered in full. (Thus to model multiple load cases, each change set requires simply the re-input of the STress resultants and/or the AXIal loading data groups, see pages 50-52.)
- (4) Rule (3) does not apply to the RESet group (see page 95). Only those variables whose values differ from those in change set 0 need appear in the RESet data input for the current change set.

- (5) Some of the program control data (see pages 32-41) is regarded as global to the problem and must not be varied in a new change set. This category includes the TITLE, VICON, VIPasa, BUCKling, VIBration, ANALysis, DESign, STABilize, FAST, PFAST, GEOMetry, ECHO and EXPlanation data. Certain RESET variables are also treated as global (see page 94), and there are restrictions (see below) on the use of the change set facility to vary quantities which control or are influenced by the design process.

The data for a change set is terminated by the CHANGE set line which introduces the next change set. The last change set may be terminated by END, which denotes the end of the whole problem.

In analysis problems, after echoing all the input data, VICONOPT calculates all the eigenvalues for the original problem (change set 0), and then repeats the process for each of the subsequent change sets. The calculation and plotting of mode shapes is deferred until the end of the analysis, and may be restricted by the requirements of the PFAST option (see page 40).

In design problems, VICONOPT attempts to find a low mass design which is stable with respect to all specified eigenvalues in all the change sets. For example, a change set might specify a new load case and/or particular values of the wavelength parameters  $\lambda$  and  $\epsilon$ . The change set facility should not be used to alter quantities associated with the design process itself, i.e. the set of design variables (SENSitivities), LINKing equations and inequality constraints, ANGLE definitions and BOUNDS on design variables (see section 5.9, pages 81-88) and the various RESET variables which control the sizing strategy (see page 95). In addition, in design problems, and in analysis problems requiring SENSitivity calculations, change sets must not be used to alter the numeric values of the design variables or of quantities linked to them. This restriction covers changes to certain PLATE breadths, LAYER properties and geometric characteristics of the panel which would otherwise be allowed in an analysis problem, and is essential to ensure that the design changes and perturbations remain consistent in all change sets.

## 6 EXAMPLE PROBLEMS

This chapter of the manual presents seven example problems which have been chosen to illustrate almost all the forms of data input described in chapter 5 (see pages 28-105). For each example, the panel geometry and loading are shown in a figure, a listing of the data input is given and explained in detail, and a selection of the printed and graphical output from VICONOPT is shown.

The first three examples describe buckling analysis problems of increasing complexity. The first uses the VIPASA-type analysis and illustrates the various methods of specifying wavelengths and the properties of plates. The second and third use the VICON-type analysis and illustrate the modelling of constraints, i.e. point supports and attachments to beam-column supporting structures. These three examples illustrate the various forms of graphical output available from VICONOPT, and together contain all the most commonly used analysis features of the program. The fourth example is an optimum design problem for which VICONOPT obtains a low-mass design which is stable with respect to a number of local (VIPASA-type) and overall (VICON-type) buckling constraints. The fifth example is a vibration problem which includes some of the less commonly used analysis features which are not described in the previous examples. The last two examples enable users to calculate machine dependent parameters which may be used in the context of section 3.5 (see pages 19-21) to estimate VICONOPT solution times for other problems.

The following general points relate to the input for all the example problems.

The data for VICONOPT may be given in any consistent system of units, with the requirements that angles are given in degrees and that in vibration problems the second is the unit of time. Units are not given in the data and do not appear in the printed results. (S.I. units are used for all the examples below).

The data input shown for the example problems appears, for clarity, in the same order as the descriptions in chapter 5 (see pages 32-105). In practice the ordering of the various data groups is unimportant. Also, with the exception of two lines in the first example, all group names and keywords are given in upper case characters for clarity, with comments in lower case. In practice any alphabetic character in the data input may appear in either upper or lower case.

### 6.1 Buckling of Lipped Channel Section

The first example problem is a VIPASA-type buckling analysis of the lipped channel section shown in figures 6.1(a)-(c), for which the data input to VICONOPT is given in figure 6.1(d). The panel is loaded in longitudinal compression with a dead load of 20kN and a live load of 100kN, the latter being factored by the load factor  $F$  until buckling occurs. It is required to find, to an accuracy of 1 part in  $10^8$ , the first two critical load factors for each of a number of half-wavelengths  $\lambda$  and to depict the results on a graph of  $F$  against  $\lambda$ . The mode shape of the overall lowest eigenvalue is to be printed and plotted, and therefore the program's use of the default value  $TOLM = .001$  (see page 102) is allowed for in the ACCuracy data input (see page 35).

Values of  $\lambda$  are specified by three different methods in the WAVelength data group (see pages 37-38): the first line of data generates the values  $\lambda = \ell/4 = 0.45\text{m}$ ,  $\lambda = \ell/5 = 0.36\text{m}$  and  $\lambda = \ell/6 = 0.30\text{m}$ , where the panel LENGth (see page 37) is  $\ell = 1.8\text{m}$ ; the second line generates the values  $\lambda = 0.50\text{m}$ ,  $\lambda = 0.60\text{m}$  and  $\lambda = 0.72\text{m}$ , using the ratio method; while the third line generates the list of values  $\lambda = 0.80\text{m}$ ,  $\lambda = 0.90\text{m}$  and  $\lambda = 1.00\text{m}$ .

The plates forming the lip, flange and web of the section are defined in three different ways using the MATerial, LAYer, WALL and PLate data groups (see pages 42-49). The lip, which has reference numbers  $n_p = 1$  in the PLate data and  $n_w = 1$  in the WALL data, is an isotropic plate of thickness 4mm made from the MATerial with reference number  $n_M = 1$ , for which  $E_1 = E_2 = 30.2\text{GNm}^{-2}$  and  $\nu_{12} = \nu_{21} = 0.31$ . The flange is



```

TITLE
EXAMPLE 6.1:  BUCKLING OF LIPPED CHANNEL SECTION
VIPASA
BUCKLING
ANALYSIS
EIGENVALUES
$ This entire line is a comment and will be ignored
1 2          $ Comments may also follow the data on a line
ACCURACY 1.E-5      $ Program will use additional accuracy of TOLM=.001
TRIAL VALUE 2.25
LENGTH 1.8
WAVELENGTH
4 6 1
R .5 .75          $ Further data may follow a comment      $ 1.2
L .8 .9 1.0
PFAST
explanation          $ Alphabetic data may be in upper or lower case
MATerial            $ or in any combination of upper and lower case
$ For clarity, lower case will only be used in comments from now on.
1 30.2E9 .31 0.
2 131.E9 .38 0. 6.41E9 13.E9
LAY                  $ Group names may be shortened to 3 characters
1 .0001397 2 45.
2 .0001397 2
3 .0012573 2 90.
WALL
ISO 1 .004 1
ANISO 2 0. 1.102E8 0.464E8 3.214E8 0.491E8 %
      197.21 101.33 280.41 103.79      $ This is a continuation line
3 1 -1 -1 1 2 3 S
PLATE
1 .02 1          $ Lip (isotropic plate)
2 .08 2          $ Flange (orthotropic plate)
3 .12 3          $ Web (laminated plate)
AXIAL LOADING
LOAD 1.E5 2.E4      $ Total live and dead longitudinal loads
ALIGNMENT
ROT 4 1 180
ROT 5 2 90
ROT 6 2 270
CONNECTIONS
1 2 4 2 3 6 4 5 5 3 4 3 5 6 4      $ Triplets can appear in any order
PLOT
-2 0 0. 1          $ Specifies mode and graph plots
END

```

(d)

Figure 6.1 (continued) (d) Data input for VICONOPT.

```

MATERIAL DATA =====
      COLUMN
      1      2      3      4      5      6
      REF      E1      NU12      RHO      E12      E2
      1  3.02000E+10  3.10000E-01  0.00000E+00  1.15267E+10  3.02000E+10
      2  1.31000E+11  3.80000E-01  0.00000E+00  6.41000E+09  1.30000E+10

LAYER DATA =====
      COLUMN
      1      2      3      4      5      6
      REF      H      MAT      THETA      TV      TF
      1  0.00014      2  4.50000E+01  0.00000E+00  0.00000E+00
      2  0.00014      2  0.00000E+00  0.00000E+00  0.00000E+00
      3  0.00126      2  9.00000E+01  0.00000E+00  0.00000E+00

WALL DATA =====
ISOTROPIC WALL NO.      1
THICKNESS      =      0.00400
MATERIAL NO.      =      1

ANISOTROPIC WALL NO.      2
MASS PER UNIT AREA      =      0.00000000

      A-STIFFNESS MATRIX      D-STIFFNESS MATRIX
      1.1020E+08  4.6400E+07  0.0000E+00  1.9721E+02  1.0133E+02  0.0000E+00
      4.6400E+07  3.2140E+08  0.0000E+00  1.0133E+02  2.8041E+02  0.0000E+00
      0.0000E+00  0.0000E+00  4.9100E+07  0.0000E+00  0.0000E+00  1.0379E+02

LAMINATED WALL NO.      3
LIST OF LAYER NUMBERS AND PROPERTIES FOLLOWS.
      COLUMN
      1      2      3      4      5      6
      REF      H      MAT      THETA      TV      TF
      1  0.00014      2  4.50000E+01  0.00000E+00  0.00000E+00
      -1  0.00014      2  -4.50000E+01  0.00000E+00  0.00000E+00
      -1  0.00014      2  -4.50000E+01  0.00000E+00  0.00000E+00
      1  0.00014      2  4.50000E+01  0.00000E+00  0.00000E+00
      2  0.00014      2  0.00000E+00  0.00000E+00  0.00000E+00
      3  0.00126      2  9.00000E+01  0.00000E+00  0.00000E+00
      3  0.00126      2  9.00000E+01  0.00000E+00  0.00000E+00
      2  0.00014      2  0.00000E+00  0.00000E+00  0.00000E+00
      1  0.00014      2  4.50000E+01  0.00000E+00  0.00000E+00
      -1  0.00014      2  -4.50000E+01  0.00000E+00  0.00000E+00
      -1  0.00014      2  -4.50000E+01  0.00000E+00  0.00000E+00
      1  0.00014      2  4.50000E+01  0.00000E+00  0.00000E+00

      TOTAL THICKNESS      =      3.9116E-03
      REFERENCE SURFACE IS 1.9558E-03 BELOW UPPER SURFACE
      MASS PER UNIT AREA      =      0.00000E+00

      A-STIFFNESS MATRIX      D-STIFFNESS MATRIX
      1.2108E+08  5.0458E+07  5.8208E-11  2.2698E+02  1.1251E+02  6.5278E-01
      5.0458E+07  3.8867E+08  1.6298E-09  1.1251E+02  3.2664E+02  6.5278E-01
      5.8208E-11  1.6298E-09  5.5927E+07  6.5278E-01  6.5278E-01  1.1948E+02

      B-STIFFNESS MATRIX      THERMAL LOADING TERMS
      3.6380E-12 -1.8190E-12 -1.1384E-13 0.0000E+00 0.0000E+00
      -1.8190E-12 0.0000E+00 -4.3598E-15 0.0000E+00 0.0000E+00
      -1.1384E-13 -4.3598E-15 0.0000E+00 0.0000E+00 0.0000E+00

      VARIABLE      FIXED
      0.0000E+00 0.0000E+00
      0.0000E+00 0.0000E+00
      0.0000E+00 0.0000E+00

PLATE DATA =====
      COLUMN
      1      2      3      4      5      6      LIVE LOADS      DEAD LOADS
      REF      B      WAL      STR      FOU      DIV      NL      NL
      1  2.00000E-02      1  0  0  0  3.43808E+05  6.87616E+04
      2  8.00000E-02      2  0  0  0  2.94574E+05  5.89148E+04
      3  1.20000E-01      3  0  0  0  3.25965E+05  6.51930E+04

```

(c)

Figure 6.1 (continued) (e) Part of the organized listing.

CHANGE SET	(VICON)	(VIPASA)	(REPET.)	EIGENVALUE	BEST ESTIMATE	TOTAL	ITEMS
SET	XI	LAMBDA	ETA	NUMBER	OF FACTOR	AXIAL LOAD	TAKEN
0	--	4.5000E-01	0.0000	2	2.478775427E+00	2.6787754E+05	11
0	--	4.5000E-01	0.0000	1	1.601161823E+00	1.8011618E+05	6
0	--	3.6000E-01	0.0000	2	2.455222443E+00	2.6552224E+05	11
0	--	3.6000E-01	0.0000	1	1.675493975E+00	1.8754940E+05	6
0	--	3.0000E-01	0.0000	2	2.599694055E+00	2.7996941E+05	14
0	--	3.0000E-01	0.0000	1	1.815302281E+00	2.1153023E+05	7
0	--	5.0000E-01	0.0000	2	2.489975924E+00	2.6899759E+05	11
0	--	5.0000E-01	0.0000	1	1.651274200E+00	1.8512742E+05	5
0	--	5.0000E-01	0.0000	1	2.338837845E+00	2.5388378E+05	11
0	--	6.0000E-01	0.0000	2	2.872836487E+00	3.0728365E+05	7
0	--	6.0000E-01	0.0000	1	2.263773764E+00	2.4637738E+05	9
0	--	7.2000E-01	0.0000	1	1.936217335E+00	2.1362173E+05	7
0	--	7.2000E-01	0.0000	2	2.533930595E+00	2.7339306E+05	11
0	--	8.0000E-01	0.0000	1	1.657165168E+00	1.8571652E+05	5
0	--	9.0000E-01	0.0000	2	2.735158773E+00	2.9351588E+05	10
0	--	9.0000E-01	0.0000	1	1.356299414E+00	1.5562994E+05	5
0	--	1.0000E+00	0.0000	2	2.622427447E+00	2.8224274E+05	12
0	--	1.0000E+00	0.0000	1	1.115063171E+00	1.3150632E+05	4

# MODE SHAPES

CHANGE SET = 0 LAMBDA = 1.0000E+00 ETA = 0.0000E+00  
 EIGENVALUE NO. = 1  
 FACTOR = 1.11506317E+00

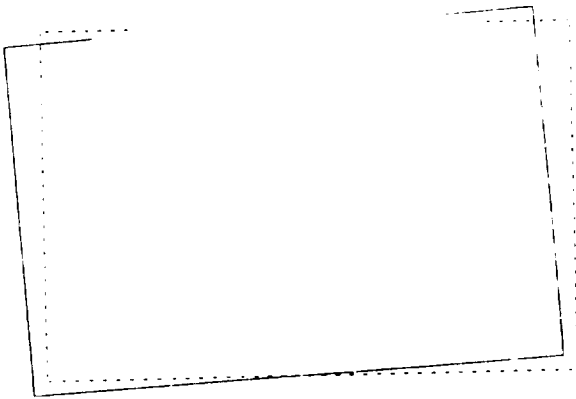
THE MODE SHAPE IS AS FOLLOWS

POINT	NODE	REAL MODE			
		X DEFLECTION (I+U)	Y DEFLECTION (V)	Z DEFLECTION (W)	CLOCKWISE ROT. (PSI)
1	1	-1.1088838E-03	-1.2310041E-02	2.8234452E-03	-9.9384756E-02
2	2	-3.3929077E-04	-1.2324086E-02	4.8156162E-03	-1.0000000E-01
3	3	8.4635735E-04	-4.6102359E-03	4.8068186E-03	-8.7198264E-02
4	4	-8.4635735E-04	-4.6102359E-03	-4.8068186E-03	-8.7198264E-02
5	5	3.3929077E-04	-1.2324086E-02	-4.8156162E-03	-1.0000000E-01
6	6	1.1088838E-03	-1.2310041E-02	-2.8234452E-03	-9.9384756E-02

IMAGINARY MODE				
X DEFLECTION (I+U)	Y DEFLECTION (V)	Z DEFLECTION (W)	CLOCKWISE ROT. (PSI)	
-1.9000692E-04	-2.1093220E-03	4.8379653E-04	-1.7029549E-02	
-5.8137376E-05	-2.1117286E-03	8.2515445E-04	-1.7134971E-02	
1.4502309E-04	-7.8996260E-04	8.2364699E-04	-1.4941398E-02	
-1.4502309E-04	-7.8996260E-04	-8.2364699E-04	-1.4941398E-02	
5.8137376E-05	-2.1117286E-03	-8.2515445E-04	-1.7134971E-02	
1.9000692E-04	-2.1093220E-03	-4.8379653E-04	-1.7029549E-02	

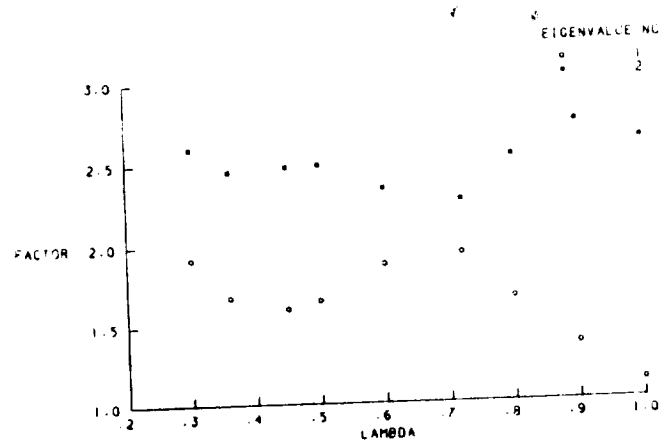
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OF POOR QUALITY

(f)



EXAMPLE 6.1: BUCKLING OF LIPPED CHANNEL SECTION  
 CHANGE SET=0 LAMBDA=1.0000 ETA=.0000  
 EIGENVALUE=1 FACTOR=1.1151 REAL MODE

(g)



EXAMPLE 6.1: BUCKLING OF LIPPED CHANNEL SECTION  
 CHANGE SET=0 ETA=.0000

(h)

Figure 6.1 (continued) (f) Eigenvalue results and mode shapes. (g) Cross-section plot of the real mode for the overall lowest eigenvalue found (which is for  $\lambda = 1.0$ ). (h) Plot of critical load factor  $F$  against half-wavelength  $\lambda$ .

defined as the anisotropic plate  $n_p = 2$ ,  $n_w = 2$ , for which the in-plane membrane and out-of-plane bending stiffness matrices are given respectively by

$$[A] = \begin{bmatrix} 110.2 & 46.4 & 0. \\ 46.4 & 321.4 & 0. \\ 0. & 0. & 49.1 \end{bmatrix} \quad \text{MNm}^{-1}$$

and

$$[D] = \begin{bmatrix} 197.21 & 101.33 & 0. \\ 101.33 & 280.41 & 0. \\ 0. & 0. & 103.79 \end{bmatrix} \quad \text{Nm}.$$

Note that VICONOPT will use orthotropic theory for this plate because  $D_{13} = D_{23} = 0$ , and that the thickness of the plate is not required in data. The web is the symmetric laminated plate  $n_p = 3$ ,  $n_w = 3$  whose layup is shown in figure 6.1(c). Each LAYer is made from the MATERIAL with reference number  $n_M = 2$ , for which  $E_1 = 131.0 \text{GNm}^{-2}$ ,  $E_2 = 13.0 \text{GNm}^{-2}$ ,  $E_{12} = 6.41 \text{GNm}^{-2}$  and  $\nu_{12} = 0.38$ , the layer thicknesses and ply angles being given in the LAYer data. Note the use of  $n_{Li} = +1$  and  $-1$  in the WALL data (see page 48) for the  $+45^\circ$  and  $-45^\circ$  layers respectively, where  $\theta = 45^\circ$  for the LAYer  $n_L = 1$  (see page 44). No density information is required for this example: the only penalty for omitting it from the MATERIAL and Anisotropic WALL data (see pages 43 and 47) is that the mass of the panel is given as zero in the program output.

Each of these three plates is defined with its y axis in the direction of the plate width, see figure 2.1(b). Referring to the node numbering of figure 6.1(b), the alignment of the section and the requirement that edge 1 of each plate is at the lower numbered of the two nodes it connects, it is apparent that the plates forming the lips and flanges must be rotated before being assembled into the panel. This is achieved in the ALIGNment data (see page 54), which defines plate 4 to represent each of the two lip portions and plates 5 and 6 to represent the two flanges in the CONNECTION data (see page 62).

The data input of figure 6.1(d) illustrates the use of upper and lower case alphabetic characters and comments as an aid to the user. VICONOPT echoes the data in an organized listing to assist in checking the input: the user is strongly advised to study this listing carefully, particularly checking that any default values supplied by the program are appropriate. Part of the organized listing for this example, covering the MATERIAL, LAYER, WALL and PLATE groups, is shown in figure 6.1(e): note that this figure has been compressed by omitting some unimportant columns from wide tables and by omitting the extra explanatory information generated by the EXPLANATION line in the input data. Note that the listing contains certain values which have been calculated by the program, e.g. the isotropic value of  $E_{12}$  for MATERIAL reference number 1, the [A] and [D] matrices and the location of the reference surface for WALL reference number 3, and the longitudinal loads per unit breadth of each plate implied by the distribution of the total loads specified in the AXIAL loading data (see page 52).

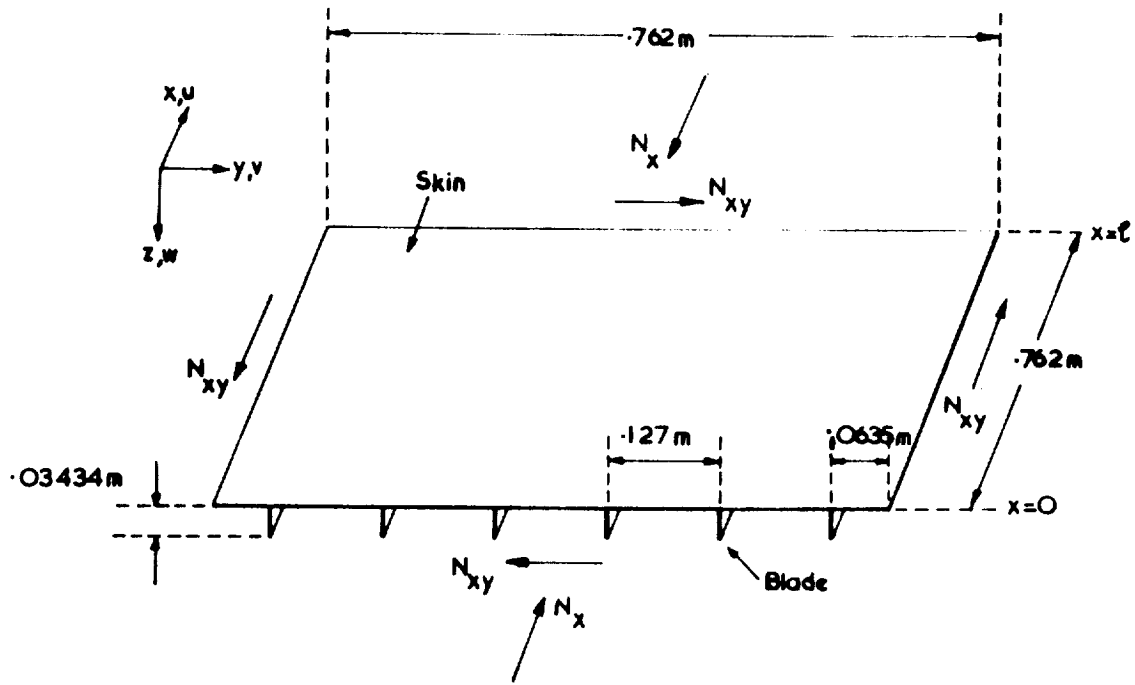
Figure 6.1(f) shows the results of the eigenvalue calculations, in the form of a table listing the two lowest critical load factors for each of the nine values of  $\lambda$  considered. The table is followed by a printout of the (complex) mode shape for the overall lowest eigenvalue (achieved by the use of the PFAST option, see page 40 and IPLOT = -2 in the PLOT data, see page 91). The real part of this mode shape is shown graphically in figure 6.1(g), while figure 6.1(h) shows the plot of  $F$  against  $\lambda$  generated by the program. An interesting feature of this plot is the apparent crossing of two smooth curves in the vicinity of  $\lambda = 0.67$ , where the shape of the critical mode changes substantially.

## 6.2 Buckling of Blade-Stiffened Panel with Constraints

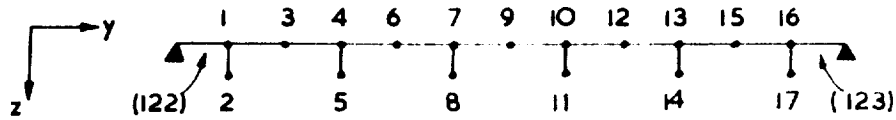
The second example problem is a VICON-type buckling analysis of the simply supported composite blade-stiffened panel shown in figures 6.2(a) and (b), for which the data input to VICONOPT is given in figure 6.2(c). (Results for an almost identical panel were also given in reference 1). The skin is loaded in shear with a live load  $N_{xy} = 175.13 \text{ kNm}^{-1}$ . A compressive longitudinal live load  $N_x$  per unit breadth of the skin is also applied to the panel: the analysis covers the two load cases  $N_x = N_{xy}$  and  $N_x = 0.5N_{xy}$ . For each load case the lowest critical buckling load factor is required, and for the overall lowest eigenvalue plots are required of the mode shape and perturbation stress levels. The VICON analysis will consider the 5 values  $\epsilon = 1., 0., .75, .5$  and  $.25$ . The MATERIAL properties are those given for material  $n_M = 2$  in example 6.1 (see page 112). The layup of the skin is the same as that for plate  $n_p = 3$ ,  $n_w = 3$  in example 6.1, which is shown in figure 6.1(c). The layup of the blades is obtained from that of the skin by doubling the thickness of the  $0^\circ$  layers to 2.794mm and omitting the  $90^\circ$  layers.

Figure 6.2(b) shows the node numbering used to model the panel. The ten skin portions lying between nodes 1 and 16 are each represented by the PLATE with reference number  $n_p = 1$ ,  $n_w = 1$ , while the six blades are each represented by plate 5, which is derived by rotation from the plate  $n_p = 2$ ,  $n_w = 2$ . The automatic data generation facility (see page 103) is used to abbreviate the input in the CONNECTIONS data group. The two end portions of skin are represented by singly connected substructures numbered 122 and 123 which are ATTACHED to nodes 1 and 16 respectively. Because such a substructure is connected to the parent structure at its final node  $N_{sub}$  (see page 152), the skin portion used in substructure 123 must be rotated by  $180^\circ$  (see plate 3 in the ALIGNMENT data). In order to match the rest of the skin, this must be derived from a skin portion (i.e.  $n_p = 4$ ,  $n_w = 3$  in the PLATE data) with reversed ply angles and shear loading.

The shear loading is given directly for each of the skin plates in the STRESS resultants data. The blades ( $n_p = 2$ ) have no shear load and so  $n_N$  (see page 49) is omitted for this PLATE. As in example 6.1 (see page 113), the



(a)



(b)

Figure 6.2 Blade-stiffened panel with constraints.  
 (a) Isometric view showing dimensions and loading.  
 (b) Cross-section, showing node numbering 1-17, longitudinal line supports (solid triangles) and point supports (solid circles). The two singly connected substructures used are identified and numbered in parentheses.

```

TITLE
EXAMPLE 6.2:  BUCKLING OF BLADE-STIFFENED PANEL WITH CONSTRAINTS
VICON 5
$ Comment: note BUCKling and ANALysis assumed by default
LENGTH .762
FAST          $ Find lowest eigenvalue for each change set
PFAST 3       $ Find and plot mode shape for lowest overall
MATERIALS
1 131.E9 .38 0. 6.41E9 13.E9
LAYERS
1 .0001397 1 45.
2 .0001397 1
3 .0012573 1 90.
4 .0002794 1
WALLS
1 1 -1 -1 1 2 3 S      $ Skin
2 1 -1 -1 1 4 S      $ Blade
3 -1 1 1 -1 2 3 S     $ Skin with reversed layup
PLATES
1 .0635 1 1 0 2      $ Skin
2 .03434 2          $ Blade
4 .0635 3 2          $ Skin with reversed shear loading and layup
STRESS RESULTANTS
1 0. -175130.        $ Shear load in skin
2 0. 175130.
AXIAL LOADING
LOAD 133449.06       $ Total longitudinal load
ALIGNMENT
ROT 3 4 180
ROT 5 2 270
122 1 901
123 3 901
CONNECTIONS
1 2 5 1 3 1 3 4 1    $ Nodes 1, 3 and 4 are on the skin
=(3)(3)(0)(3)(3)(0)(3)(3)(0) $ Generates 5 lines like the above line
==(5)
16 17 5
ATTACHMENTS
1 122 16 123
LONGITUDINAL LINE SUPPORTS
3
POINT SUPPORTS
3
1 3 4 6 7 9 10 12 13 15 16
2
2 5 8 11 14 17
PLOT
3 3 1. 0 3
CROSS-SECTIONAL PLOTTING
1 2
NODES
1 3 4 6 7 9 10 12 13 15 16
RESET
NUMX=30 NUMY=30 ISYM2=16
CHANGE SET 1
$ This change set defines a new load case, in which the longitudinal
$ loading is halved, but the shear loading remains the same.
AXIAL LOADING
LOAD 66724.53
END

```

(c)

Figure 6.2 (continued) (c) Data input for VICONOPT.

CHANGE SET	(VICON) XI	(VIPASA) LAMBDA	(REPET.) ETA	EIGENVALUE NUMBER	BEST ESTIMATE OF FACTOR	TOTAL AXIAL LOAD	ITERS. TAKEN
0	1.0000	--	0.0000	1	9.129644887E-01	1.2183425E+05	13
0	0.0000	--	0.0000	1	EXCEEDS	9.129644869E-01	
0	0.7500	--	0.0000	1	EXCEEDS	9.129644869E-01	
0	0.5000	--	0.0000	1	EXCEEDS	9.129644869E-01	
0	0.2500	--	0.0000	1	EXCEEDS	9.129644869E-01	
1	1.0000	--	0.0000	1	1.533722185E+00	1.0233689E+05	14
1	0.0000	--	0.0000	1	EXCEEDS	1.533722182E+00	
1	0.7500	--	0.0000	1	2 1.285023991E+00	8.5742622E+04	13
1	0.5000	--	0.0000	1	EXCEEDS	1.285023991E+00	
1	0.2500	--	0.0000	1	EXCEEDS	1.285023991E+00	

(d)

EXAMPLE 6.2: BUCKLING OF BLADE-STIFFENED PANEL WITH CONSTRAINTS  
CHANGE SET=0

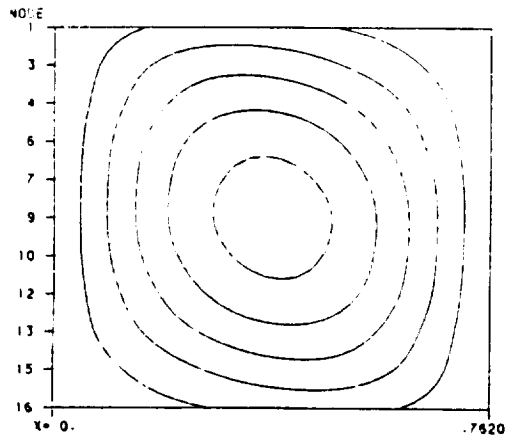
CROSS-SECTION OF PLATE NO. 2



(e)

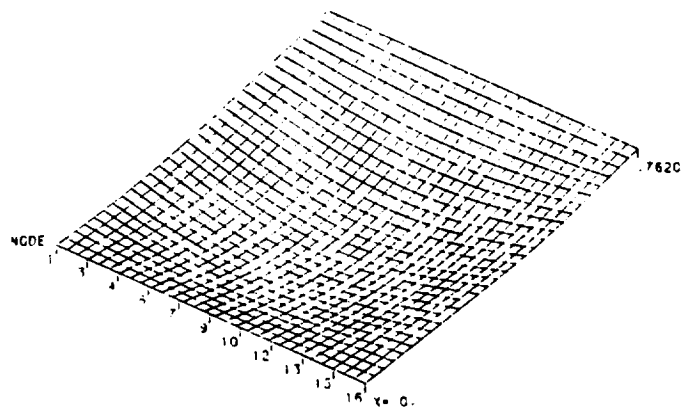
Figure 6.2 (continued) (d) Results of VICONOPT eigenvalue calculations. (e) Cross-section plot showing the layup of plate 2.

EXAMPLE 6.2: BUCKLING OF BLADE-STIFFENED PANEL WITH CONSTRAINTS  
 CHANGE SET=0 X1=1.0000 ETA=.0000  
 EIGENVALUE=1 FACTOR=.9130 DISPLACEMENT W  
 MAX HEIGHT=.0254 MIN HEIGHT=.0.0000 INTERVAL=.0048



(f)

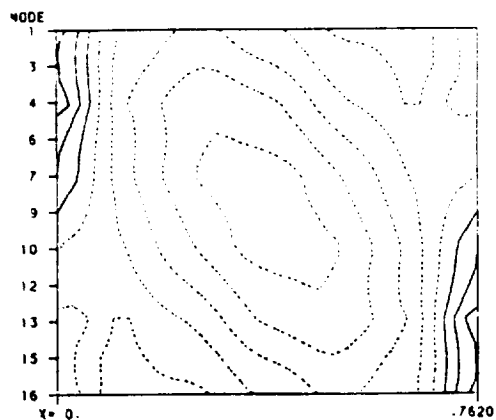
EXAMPLE 6.2: BUCKLING OF BLADE-STIFFENED PANEL WITH CONSTRAINTS  
 CHANGE SET=0 X1=1.0000 ETA=.0000  
 EIGENVALUE=1 FACTOR=.9130 DISPLACEMENT W  
 ISOMETRIC PLOT



(g)

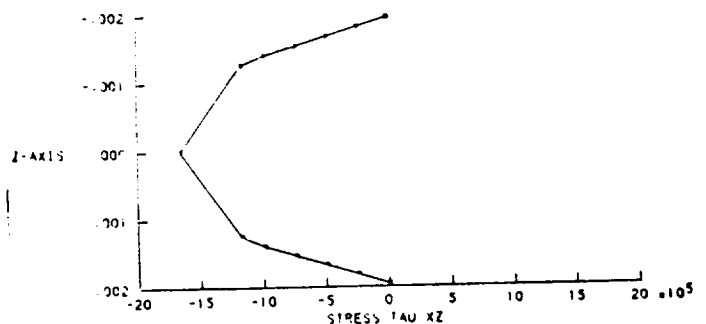
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 OF POOR QUALITY

EXAMPLE 6.2: BUCKLING OF BLADE-STIFFENED PANEL WITH CONSTRAINTS  
 CHANGE SET=0 X1=1.0000 ETA=.0000  
 EIGENVALUE=1 FACTOR=.9130 STRESS SIGMA 1  
 CONTOUR PLOT AT LAYER NUMBER=2 Z=.001327  
 MAXIMUM=120487081 MINIMUM=-2.455E+09 INTERVAL=44632623



(h)

EXAMPLE 6.2: BUCKLING OF BLADE-STIFFENED PANEL WITH CONSTRAINTS  
 CHANGE SET=0 X1=1.0000 ETA=.0000  
 EIGENVALUE=1 FACTOR=.9130 STRESS SIGMA 2  
 VERTICAL SECTION AT X=.053 Y=.131



(i)

Figure 6.2 (continued) (f) Contour and (g) isometric plots of displacement  $w$  at the overall lowest mode. (h) Contour plot of the perturbation stress level  $\sigma_1$  in the upper  $0^\circ$  layer of skin. (i) Section plot of the perturbation stress level  $\tau_{xy}$  at the point  $x = .053$ ,  $y = .131$ , at the overall lowest mode. (Negative contours shown dashed.)

longitudinal load in each plate is calculated by the program from the total load given in the AXIAL loading data (see page 52), whose value here is  $N_x$  multiplied by the breadth of the skin (0.762m).

The simple supports on the longitudinal edges are modelled exactly as LONGitudinal line supports (see page 65) which suppress  $w$  displacement. These are included by means of the 901 entries in the single connected substructure specifications in the ALIGNment data (see page 58). The simple supports on the transverse edges are modelled approximately by a set of 17 point supports as shown in figure 6.2(b): those on the skin suppress  $w$  displacement and those at the tips of the blades suppress  $v$  displacement. These are entered for the edge  $x = 0$  using the POINT supports data (see pages 66-67), and their repetition at longitudinal intervals of  $l$  is assumed by the program.

Figure 6.2(d) lists the VICONOPT eigenvalue results. The basic problem (change set 0) covers the load case  $N_x = N_{xy}$ , and the load case  $N_x = 0.5N_{xy}$  is appended to the data as CHANGE set 1 (see page 41). Note the effects of the FAST option (see page 39) in reducing the number of eigenvalues which have to be calculated.

For the overall lowest eigenvalue (since the option PFAST 3 is used, see page 40), the PLOT data (see page 91) specifies a cross-section plot of the deflected mode shape at  $x = l/2$  (which is the default XLocation, see page 36). In addition, for the skin between nodes 1 and 16 (see the NODES data, page 93), contour and isometric plots will be made of the  $w$  displacement and the perturbation stress levels will be shown in contour and section plots. For all these plots a 30 x 30 grid will be used (see NUMX and NUMY in the RESET data, page 99), while the setting ISYM2 = 16 is needed to obtain a point symmetric mode (nodes 1 and 16 being symmetrically placed, see page 98). For increased accuracy in the perturbation stress calculations, displacements will be calculated at the mid-point of each plate (since  $n_g = 2$  in the PLATE data, see page 49). The CROSS-sectional plotting data (see page 92) specifies detailed views showing the layups of plates 1 and 2: that for the blade (plate 2) is shown in figure 6.2(e), while some of the mode plots are given in figures 6.2(f)-(i).

### 6.3 Buckling of Corrugated Cylinder with Ring Stiffeners

The third example problem is a VICON-type buckling analysis of a corrugated cylinder with ring stiffeners, which was also presented in reference 1. Details of the geometry are given in figures 6.3(a) and (b), and the data input to VICONOPT is shown in figure 6.3(c). The panel is loaded in shear with a live load  $N_{xy} = 175.13 \text{ kN}_m^{-1}$ , and with a compressive load  $N_x$  per unit breadth whose live component is such as will produce a uniform axial strain  $\epsilon = .001823$  and whose dead component is caused by a temperature rise of 100C degrees. The ring stiffeners are unloaded. It is required to find the overall lowest critical buckling load factor  $F$ .

The cylinder is modelled efficiently using cylindrical coordinate transformations (see pages 59 and 73) so that very few angles need to be calculated, and the VICONOPT repetitive analysis (see pages 77-79) which uses only a repeating portion comprising 3 nodes and the plates and ring stiffeners which extend over one interval of the corrugation. Although there are 48 such intervals around the circumference, the analysis is restricted to modes which repeat at intervals of  $2P$  repeating portions, and so the WIDTH data specifies  $P = 24$ , i.e. half the circumference, as is appropriate for a closed loop section (see section 3.4, page 17). To find the lowest buckling load, it is therefore necessary to perform separate analyses for a selection of values of  $\epsilon$  in the range  $0 \leq \epsilon \leq 1$ , and for values of  $g$  in the range  $0 \leq g \leq 24$  with corresponding negative values of  $g$  being examined automatically by the program if necessary. For the purposes of illustration, it is supposed that the user believes (e.g. from previous analysis of a similar problem) that the lowest value of  $F$  is likely to occur for  $\epsilon$  in the range  $0.6 \leq \epsilon \leq 0.8$  and for  $g$  in the range  $1 \leq g \leq 8$ . Efficient use is made of the FAST option by examining such cases first, so that the lowest value of  $F$  is found quickly and the remaining cases require only a check iteration at trial value  $F$  (see page 39). The WAVelength and TRANsverse wavelength data groups in figures 6.3(c) specify analysis of the cases  $\epsilon = 0.6, 0.65, 0.7, 0.75, 0.8, 0., 0.5, 1.$  and  $g = 0, \pm 1, \pm 2, \dots, \pm 7, \pm 8, \pm 10, \pm 12, \dots, \pm 20, \pm 22, \pm 24$  respectively. Including negative values where necessary this means that 226

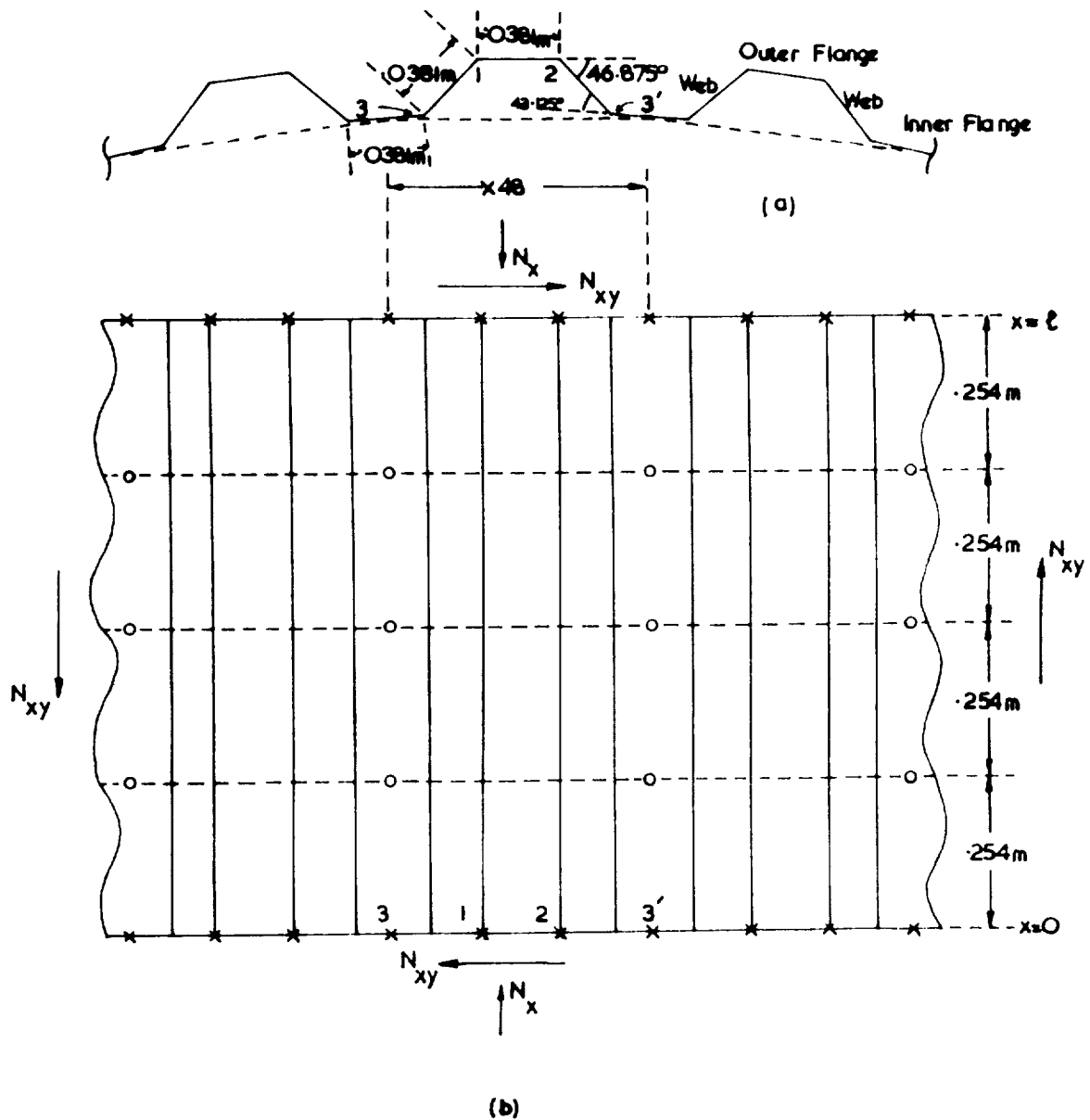


Figure 6.3 Cylinder with 48 regular corrugations and three ring stiffeners (shown dashed). (a) Detail of the corrugation cross-section, showing plate dimensions and alignment, and the node numbering, 1-3, used for one repeating portion. (Node 3' belongs to the adjacent repeating portion.) (b) Side view of the same part of the cylinder (foreshortened) showing loading conditions and node numbering, with crosses showing point supports and circles showing attachments to the ring stiffeners.

```

TITLE
EXAMPLE 6.3:  BUCKLING OF CORRUGATED CYLINDER WITH RING STIFFENERS
VICON 0 2
BUCKLING
XLOCATION
.381 .508
LENGTH 1.016
WAVELENGTH
XI 0.6 0.81 0.05 0. 1. 0.5
WIDTH 24
FAST 2
PFAST 2
MATERIALS                                     $ Note thermal properties included
1 131.E9 .38 .0 6.41E9 13.0E9 3.E-6 150.E-6
LAYERS                                         $ Note temperature rise included
1 .0001397 1 45. 0. 100.
2 .0004191 1 0. 0. 100.
WALLS
1 1 -1 -1 1 2 S
2 1 -1 -1 1 1 S
3 -1 1 1 -1 2 S
4 -1 1 1 -1 S
PLATES
1 .0381 1 1 $ Flange
2 .0381 2 1 $ Web
3 .0381 4 2 $ Web (to be reversed)
4 .01905 1 1 $ Half flange
5 .01905 3 2 $ Half flange (to be reversed)
STRESS
1 0 -175130.
2 0 175130.
AXIAL LOADING
EPS .001823
ALIGNMENT
R 6 2 -45
C 7 6 -1.875 $ Web
R 8 5 180 $ Half flange reversed
R 9 3 -135
C 10 9 1.875 $ Web reversed
11 7 4
12 10 8
CONNECTIONS
1 2 1 2 3 11 1 3 12
POINT SUPPORTS
23
1 2 3
BEAMS
1 5.20E6 439. 0. 0. 0.128208
BALIGNMENT
C 2 1 -3.75
SUPPORTING STRUCTURES
C 3 3 2
23 3
X .254 .508 .762
REPETITIVE PLATES AND BEAMS
P 11
B 2
TRANSVERSE WAVELENGTHS
0 8 1 10 24 2
PLOT
2 1 3.0
NODES
3 1 2
RESET
NWID=12 INMOD=1
NUMX=60 NUMY=120 NC=10
END

```

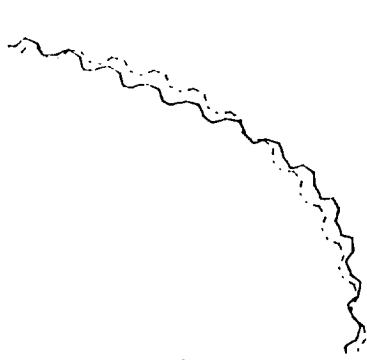
(c)

Figure 6.3 (continued) (c) Data input for VICONOPT.

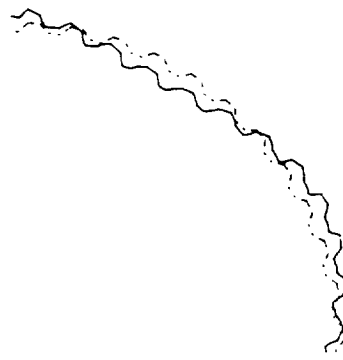
CHANGE SET	(VICON) XI	(VIPASA) LAMBDA	(REPET.) ETA	EIGENVALUE NUMBER	BEST ESTIMATE OF FACTOR	TOTAL AXIAL LOAD	ITERS. TAKEN
0	0.6000	--	0.0000	1 -	2 1.841546684E+00	4.8287053E+04	13
0	0.6000	--	0.0417	1 -	2 1.819290411E+00	4.7792180E+04	12
0	0.6000	--	-0.0417	1	EXCEEDS	1.819290410E+00	
0	0.6000	--	0.0833	1	EXCEEDS	1.819290410E+00	
0	0.6000	--	-0.0833	1	EXCEEDS	1.819290410E+00	
0	0.6000	--	0.1250	1 -	2 1.791377689E+00	4.7171533E+04	13
0	0.6000	--	-0.1250	1	EXCEEDS	1.791377688E+00	
0	0.6000	--	0.1667	1 -	2 1.391267523E+00	3.8274986E+04	13
0	0.6000	--	-0.1667	1	EXCEEDS	1.391267520E+00	
0	0.6000	--	0.2083	1 -	2 1.103879660E+00	3.1884846E+04	10
0	0.6000	--	-0.2083	1	EXCEEDS	1.103879658E+00	
0	0.6000	--	0.2500	1	EXCEEDS	1.103879658E+00	
0	0.6000	--	-0.2500	1	EXCEEDS	1.103879658E+00	
0	0.6000	--	0.2917	1	EXCEEDS	1.103879658E+00	
0	0.6000	--	-0.2917	1	EXCEEDS	1.103879658E+00	
0	0.6000	--	0.3333	1	EXCEEDS	1.103879658E+00	
0	0.6000	--	-0.3333	1	EXCEEDS	1.103879658E+00	
0	0.6000	--	0.4167	1	EXCEEDS	1.103879658E+00	
0	0.6000	--	-0.4167	1	EXCEEDS	1.103879658E+00	
0	0.6000	--	0.5000	1	EXCEEDS	1.103879658E+00	
0	0.6000	--	-0.5000	1	EXCEEDS	1.103879658E+00	
0	0.6000	--	0.5833	1	EXCEEDS	1.103879658E+00	
0	0.6000	--	-0.5833	1	EXCEEDS	1.103879658E+00	
0	0.6000	--	0.6667	1	EXCEEDS	1.103879658E+00	
0	0.6000	--	-0.6667	1	EXCEEDS	1.103879658E+00	
0	0.6000	--	0.7500	1	EXCEEDS	1.103879658E+00	
0	0.6000	--	-0.7500	1	EXCEEDS	1.103879658E+00	
0	0.6000	--	0.8333	1	EXCEEDS	1.103879658E+00	
0	0.6000	--	-0.8333	1	EXCEEDS	1.103879658E+00	
0	0.6000	--	0.9167	1	EXCEEDS	1.103879658E+00	
0	0.6000	--	-0.9167	1	EXCEEDS	1.103879658E+00	
0	0.6000	--	1.0000	1	EXCEEDS	1.103879658E+00	
0	0.6500	--	0.0000	1	EXCEEDS	1.103879658E+00	
0	0.6500	--	0.0417	1	EXCEEDS	1.103879658E+00	
0	0.6500	--	-0.0417	1	EXCEEDS	1.103879658E+00	
0	0.6500	--	0.0833	1	EXCEEDS	1.103879658E+00	
0	0.6500	--	-0.0833	1	EXCEEDS	1.103879658E+00	
0	0.6500	--	0.1250	1	EXCEEDS	1.103879658E+00	
0	0.6500	--	-0.1250	1	EXCEEDS	1.103879658E+00	
0	0.6500	--	0.1667	1	EXCEEDS	1.103879658E+00	
0	0.6500	--	-0.1667	1	EXCEEDS	1.103879658E+00	
0	0.6500	--	0.2083	1 -	2 1.097559924E+00	3.1744325E+04	8
0	0.6500	--	-0.2083	1	EXCEEDS	1.097559923E+00	
0	0.6500	--	0.2500	1	EXCEEDS	1.097559923E+00	
0	0.6500	--	-0.2500	1	EXCEEDS	1.097559923E+00	
0	0.6500	--	0.2917	1	EXCEEDS	1.097559923E+00	
0	0.6500	--	-0.2917	1	EXCEEDS	1.097559923E+00	
... (176 lines omitted)							
0	1.0000	--	0.8333	1	EXCEEDS	1.097559923E+00	
0	1.0000	--	0.9167	1	EXCEEDS	1.097559923E+00	
0	1.0000	--	1.0000	1	EXCEEDS	1.097559923E+00	

(d)

Figure 6.3 (continued) (d) Eigenvalue results, showing the efficient use of the FAST option in searching for the lowest critical load factor over combinations of  $\epsilon$  and  $\eta$  ( $= \epsilon/P$ ).

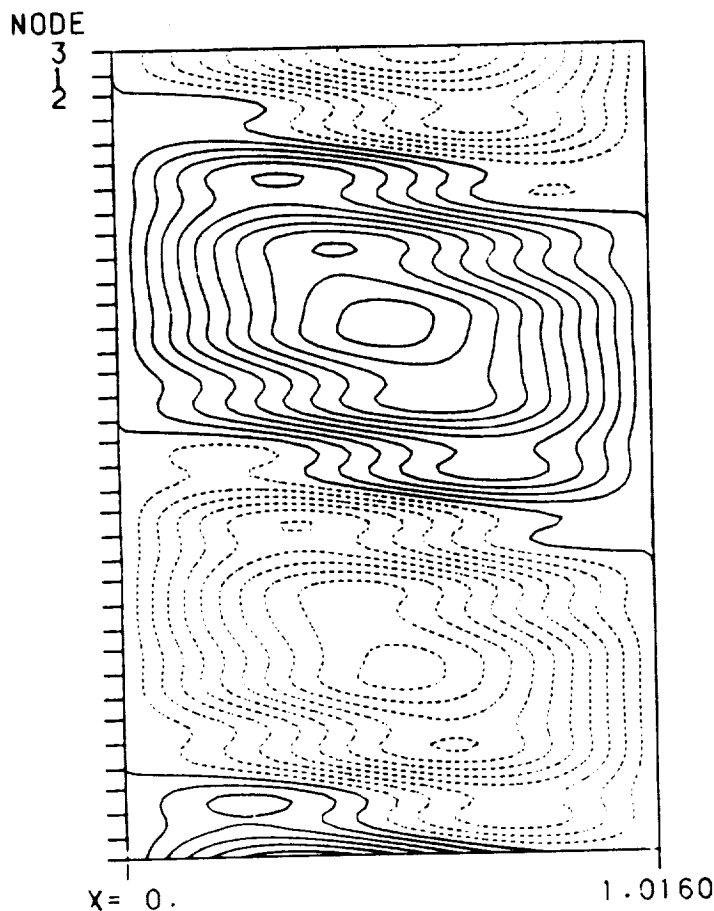


(e)



(f)

EXAMPLE 6.3: BUCKLING OF CORRUGATED CYLINDER WITH RING STIFFENERS  
 CHANGE SET=0       $X1=.6500$        $ETA=.2083$   
 EIGENVALUE=1      FACTOR=1.0976      DISPLACEMENT W  
 MAX HEIGHT=.0185      MIN HEIGHT=-.0184      INTERVAL=.0018



(g)

Figure 6.3 (continued) Deflected shape of 1/4 of the circumference, showing cross-sections (e) midway between ring stiffeners ( $x = .381$ ) and (f) at a ring stiffener ( $x = .508$ ). (g) Contour plot of radial displacements of 1/4 of the circumference. (Negative contours shown dashed.)

combinations must be considered, but the efficient ordering means that only the 6 eigenvalues listed in figure 6.3(d) were actually found, the remainder being eliminated by check iterations.

The MATERIAL properties for the panel are the same as those used in Example 6.2 (see page 114), with the thermal properties given by  $\alpha_1 = 3 \cdot 10^{-6}/\text{C degree}$ ,  $\alpha_2 = 150 \cdot 10^{-6}/\text{C degree}$  (see page 43). The layup matches that of the blades in Example 6.2 (see page 114), except that for the flange portions the thickness of the  $0^\circ$  layers is increased by 50% to 4.191mm and for the web portions the  $0^\circ$  layers are omitted. As in Example 6.2, PLATES which are to be reversed in the ALIGNMENT data are entered with reversed ply angles and shear loading.

The ALIGNMENT and BALIGNMENT data in figure 6.3(c) may be understood by analogy with the example given in section A2.5 of Appendix 2 (see pages 161-163). The cylindrical coordinate transformations used in this example are applied only to the web portions, and so the y axis at each of the nodes in figure 6.3(a) is parallel to the flange at that node. Thus the y axes at nodes 3 and 3' are rotated by  $+3.75^\circ$  and  $-3.75^\circ$  respectively relative to the y axis which is common to nodes 1 and 2, with clockwise angles given positive. Using the notation of section A2.5, therefore, the web portion starting at node 2 has rotation  $\phi = -46.875^\circ$  and the axis rotations at its edges are  $\phi_1 = 0^\circ$ ,  $\phi_2 = -3.75^\circ$ : hence  $\mu_1 = -46.875^\circ$ ,  $\mu_2 = -43.125^\circ$  and the portion is ALIGNED (as plate 7) by applying a rotation  $\mu_R = -45^\circ$  and a cylindrical coordinate transformation  $\mu_C = -1.875^\circ$ . The reversed web portion starting at node 1 is ALIGNED similarly (as plate 10). Each of these is next combined with half of the inner flange to give a simple doubly connected substructure (reference numbers 11 and 12). The ring stiffener portion joining nodes 3 and 3' has  $\phi = 0^\circ$ ,  $\phi_1 = 3.75^\circ$ ,  $\phi_2 = -3.75^\circ$  resulting in  $\mu_R = 0^\circ$ ,  $\mu_C = -3.75^\circ$  and so the BALIGNMENT data consists of just one cylindrical coordinate transformation.

The BEAMS data (see page 69) defines the properties of this ring stiffener portion:  $EA = 5.20\text{MN}$ ,  $EI = 439\text{Nm}^2$  and length  $L = .128208\text{m}$  (calculated by the user). The SUPPORTING structures data defines firstly the connection list for a

ring stiffener (note that the only connection goes from node 3 in the basic repeating portion to node 3 in the next repeating portion and so beam 2 appears, like plate 11, in the REPetitive plates and beams data, see pages 77-78), secondly the attachment of freedoms v and w of the ring stiffener to those of the panel at node 3, and thirdly the occurrence of the ring stiffener at the three longitudinal positions shown in figure 6.3(b).

For the overall lowest critical buckling load, mode shapes are plotted at the two longitudinal positions given in the XLOcation data (i.e. midway between and at the ring stiffener attachments), with an exaggerated amplitude specified by AMP = 3.0 in the PLOt data (see page 91). These plots, shown in figures 6.3(e) and (f), cover 12 repeating portions and include accurate displacements at the internal modes of substructures 11 and 12 (see NWID and INMOD in the RESet data, pages 100 and 97). A contour plot is also drawn over 12 repeating portions, the NODEs data (see page 93) being essential here to give the correct ordering of the nodes around the circumference. The RESet variables NUMX, NUMY and NC (see page 99) control the appearance of the contour plot, which is shown in figure 6.3(g). The use of a fine grid and many contours illustrates local variations in the deflected shape caused by the attachment of the ring stiffeners. In contrast, the wrinkled contours in figure 7.2(c) of reference 1 were due simply to different displacements on the inner and outer flanges: an earlier program error had resulted in the ring stiffeners being effectively ignored, and the mode given there was not in fact that for the lowest buckling load over all relevant values of  $\epsilon$  and  $g$ .

#### 6.4 Optimum Design of J-Stiffened Panel

This example illustrates the use of VICONOPT for optimum design, and is similar to example 4 of reference 2. A stable, low-mass design is sought for the J-stiffened panel shown in figures 6.4(a)-(c), for which the data input is given in figure 6.4(d). The panel is required to carry a longitudinal load of 1921.63kN and a shear load  $N_{xy} = 788.07\text{kNm}^{-1}$ : these are entered as live load values, and the program ensures stability by designing the panel such that the lowest critical load factor is unity.

Details of the layups used are shown in figure 6.4(c). All  $0^\circ$  plies are made from MATerial reference  $n_M = 1$ , for which (see page 43)  $E_1 = 220.632\text{GNm}^{-2}$ ,  $E_2 = 18.6159\text{GNm}^{-2}$ ,  $E_{12} = 6.41213\text{GNm}^{-2}$ ,  $\nu_{12} = 0.21$  and  $\rho = 1584\text{kgm}^{-3}$ . The remaining plies use MATerial  $n_M = 2$ , for which  $E_1 = 75.8424\text{GNm}^{-2}$ ,  $E_2 = 5.51581\text{GNm}^{-2}$ ,  $E_{12} = 2.06843\text{GNm}^{-2}$ ,  $\nu_{12} = 0.34$  and  $\rho = 1584\text{kgm}^{-3}$ . The identification numbers (1)-(3) appear in the data as both WALL and PLate reference numbers. PLate 4 comprises layups (1) and (2) bonded together. It is not symmetric so its [B] matrix does not vanish, even after the automatic application of the procedure described in Appendix 1 (see page 150): this causes VICONOPT to print a warning message (see the RESet variable TOLB, page 101). PLates 5 and 6 are copies of plates 1 and 4 having reversed layups and shear loading, which will be rotated by  $180^\circ$  in the ALIGNment data.

The design variables for the problem comprise the breadths of PLates 1-3 and all seven independent LAYer thicknesses (note LAYers 4 and 6 are used in both of WALLs 2 and 3). These are identified in the SENSitivities data group (see page 81), and some of them are given bounds using the BOUNDS data group (see pages 87-88). The LINKing data (see pages 82-84) specifies the following logical requirements which must be satisfied by any design change:



```

TITLE
EXAMPLE 6.4: OPTIMUM DESIGN OF J-STIFFENED PANEL
VICON 5 2
VIPASA
BUCKLING
DESIGN 6 4
ACCURACY 1.E-5
LENGTH 0.762
WAVELENGTH
R 0.0254 0.254 1.5
L 0.254
FAST
PFAST
MATERIALS
1 220.632E9 0.21 1584. 6.41213E9 18.6159E9
2 75.8424E9 0.34 1584. 2.06843E9 5.51581E9
LAYERS
1 0.0010160 2 45
2 0.0003048 1 0
3 0.0002032 2 90
4 0.0002032 2 45
5 0.0017760 1 0
6 0.0002032 2 90
7 0.0004064 1 0
WALLS
1 1 -1 2 3 S
2 4 -4 5 6 S
3 4 -4 7 6 S
4 1 -1 2 3 3 2 -1 1 4 -4 5 6 6 5 -4 4
5 -1 1 -2 -3 S
6 -4 4 -5 -6 -6 -5 4 -4 -1 1 -2 -3 -3 -2 1 -1
PLATES
1 0.05080 1 1
2 0.01016 2
3 0.03048 3
4 0.02540 4 1
5 0.05080 5 2
6 0.02540 6 2
STRESS
1 0.0 788070.
2 0.0 -788070.
AXIAL LOADING
LOAD 1921630
ALIGNMENT
OFF 7 4 0.0 -.0023876 0.0 -.0023876
OFF 8 6 0.0 .0023876 0.0 .0023876
ROT 9 3 90
OFF 10 9 0.0 0.0 0.0 -0.0073152
OFF 11 2 0.0 0.0 0.001016 0.0
121 11 10
12 7 121 1 1 7
122 1 901 7
13 5 8
ROT 14 13 180
123 14 901
CONNECTIONS
1 2 12 2 3 12 3 4 12 4 5 12 5 6 12 6 7 12 7 8 12
ATTACHMENTS
1 122 8 121 8 123
LONGITUDINAL LINE SUPPORTS
3
POINT SUPPORTS
3
1 2 3 4 5 6 7 8
SENSITIVITIES
B 1 2 3
T 1 2 3 4 5 6 7
LINKING
1 OZ1 7 E -2 T 4 -1 T 5 -1 T 6
1 OZ2 7 -1 OZ1 7 E 0
1 OZ1 8 1 OZ1 7 E 0
1 OZ2 8 1 OZ1 7 E 0
1 OZ2 10 E -2 T 1 -1 T 2 -1 T 3 -4 T 4 -2 T 5 -2 T 6
1 OY2 11 E 2 T 4 1 T 6 1 T 7
1 B 5 E 1 B 1
1 B 4 E -1 B 1 0.07620
1 B 6 -1 B 4 E 0.00
6 T 4 3 T 5 3 T 6 4 T 1 2 T 2 2 T 3 1 B 3 L 0.06
BOUNDS
BU 1 0.06620
TL 1 0.0000762 2 0.0000762 3 0.0000762 %
4 0.0000762 5 0.0000762 6 0.0000762 7 0.0000762
PLOT
1
CROSS-SECTIONAL PLOTTING
1 2 3
END

```

(d)

Figure 6.4 (continued) (d) Data input for VICONOPT.

INITIAL MASS = 1.0885E+01

INITIAL ANALYSIS

CHANGE	(VICON)	(VIPASA)	(REPET.)	EIGENVALUE	BEST ESTIMATE	TOTAL	ITEMS.
SET	XI	LAMBDA	ETA	NUMBER	OF FACTOR	AXIAL LOAD	TAKEN
0	--	2.5400E-02	0.0000	1	- 8	3.643408015E+00	7.0012821E+06 19
0	--	3.8100E-02	0.0000	1		EXCEEDS 3.643383413E+00	
0	--	5.7150E-02	0.0000	1		3.166875893E+00	6.0855637E+06 14
0	--	8.5725E-02	0.0000	1		2.191583127E+00	4.2114119E+06 12
0	--	1.2859E-01	0.0000	1		1.581953242E+00	3.0399288E+06 12
0	--	1.9288E-01	0.0000	1		1.084486088E+00	2.0839810E+06 13
0	--	2.5400E-01	0.0000	1		8.562220754E-01	1.6453420E+06 10
0	1.0000	--	0.0000	1		6.097185895E-01	1.1716535E+06 15
0	0.0000	--	0.0000	1		EXCEEDS 6.097177558E-01	
0	0.7500	--	0.0000	1	- 2	5.712551759E-01	1.0977411E+06 11
0	0.5000	--	0.0000	1		EXCEEDS 5.712440170E-01	
0	0.2500	--	0.0000	1		EXCEEDS 5.712440170E-01	

INITIAL STABILIZATION

CHANGE	(VICON)	(VIPASA)	(REPET.)	EIGENVALUE	THICKNESS	MASS AFTER
SET	XI	LAMBDA	ETA	NUMBER	FACTOR	STABILIZATION
0	0.7500	--	0.0000	1	1.348632813E+00	1.4679252E+01
0	1.0000	--	0.0000	1	1.004882813E+00	1.4750928E+01

VALUES OF DESIGN VARIABLES:

5.080000000E-02 1.016000000E-02 3.048000000E-02 1.376901421E-03 4.130704262E-04  
2.753802841E-04 2.753802841E-04 2.409577486E-03 2.753802841E-04 5.507605662E-04

MASS AFTER INITIAL STABILIZATION = 1.4751E+01

CONSTRAINT AND SENSITIVITY ANALYSIS - SIZING CYCLE 1

CHANGE	(VICON)	(VIPASA)	(REPET.)	EIGENVALUE	BEST ESTIMATE	TOTAL	ITEMS.
SET	XI	LAMBDA	ETA	NUMBER	OF FACTOR	AXIAL LOAD	TAKEN
0	1.0000	--	0.0000	1	1.000356025E+00	1.9223141E+06	15
0	0.7500	--	0.0000	1	1.009720357E+00	1.9403089E+06	13
0	0.5000	--	0.0000	1	1.111254510E+00	2.1354200E+06	13

CONMIN OPTIMIZATION - SIZING CYCLE 1 CONMIN CYCLE 1

SIZING CYCLE MOVE LIMIT FACTOR = 4.5000E-01  
CONMIN CYCLE MOVE LIMIT FACTOR = 1.0000E+00

MASS AFTER CONMIN OPTIMIZATION = 8.5926E+00

STABILIZATION - SIZING CYCLE 1 CONMIN CYCLE 1

CHANGE	(VICON)	(VIPASA)	(REPET.)	EIGENVALUE	THICKNESS	MASS AFTER
SET	XI	LAMBDA	ETA	NUMBER	FACTOR	STABILIZATION
0	1.0000	--	0.0000	1	1.381835938E+00	1.1873611E+01

VALUES OF DESIGN VARIABLES:

6.820000000E-02 5.588000000E-03 4.419600000E-02 1.046458526E-03 3.139375578E-04  
2.092917052E-04 2.092917052E-04 4.827979108E-03 2.092917052E-04 1.103538082E-03

MASS AFTER STABILIZATION = 1.1874E+01

CONMIN OPTIMIZATION - SIZING CYCLE 1 CONMIN CYCLE 2

SIZING CYCLE MOVE LIMIT FACTOR = 4.5000E-01  
CONMIN CYCLE MOVE LIMIT FACTOR = 5.0000E-01  
MASS AFTER CONMIN OPTIMIZATION = 1.1359E+01

STABILIZATION - SIZING CYCLE 1 CONMIN CYCLE 2

CHANGE	(VICON)	(VIPASA)	(REPET.)	EIGENVALUE	THICKNESS	MASS AFTER
SET	XI	LAMBDA	ETA	NUMBER	FACTOR	STABILIZATION
0	1.0000	--	0.0000	1	1.049804688E+00	1.1924416E+01
0	0.7500	--	0.0000	1	1.000976563E+00	1.1936081E+01

VALUES OF DESIGN VARIABLES:

6.223000000E-02 7.874000000E-03 3.733800000E-02 1.121339103E-03 3.364017308E-04  
2.242678205E-04 2.787981841E-04 2.992224322E-03 2.242678205E-04 7.089756907E-04

MASS AFTER STABILIZATION = 1.1936E+01

(e)

Figure 6.4 (continued) (e) Selected VICONOPT output: initial analysis and stabilization, followed by the first two CONMIN cycles of the first sizing cycle.

# CONMIN OPTIMIZATION - SIZING CYCLE 4 CONMIN CYCLE 2

SIZING CYCLE MOVE LIMIT FACTOR = 4.5000E-01  
 CONMIN CYCLE MOVE LIMIT FACTOR = 3.6450E-01  
 MASS AFTER CONMIN OPTIMIZATION = 1.1328E+01

## STABILIZATION - SIZING CYCLE 4 CONMIN CYCLE 2

CHANGE SET	(VICON) XI	(VIPASA) LAMBDA	(REPET.) ETA	EIGENVALUE NUMBER	THICKNESS FACTOR	MASS AFTER STABILIZATION
0	0.7500	--	0.0000	1	1.032226563E+00	1.1693178E+01
0	1.0000	--	0.0000	1	1.004882813E+00	1.1750273E+01

VALUES OF DESIGN VARIABLES:  
 8.619999967E-02 4.452910994E-03 3.415536514E-02 1.166755456E-03 3.206001890E-04  
 1.534982742E-04 4.365102896E-04 3.651511716E-03 1.755003150E-04 8.730205791E-04

MASS AFTER STABILIZATION = 1.1750E+01

# CONMIN OPTIMIZATION - SIZING CYCLE 4 CONMIN CYCLE 3

SIZING CYCLE MOVE LIMIT FACTOR = 4.5000E-01  
 CONMIN CYCLE MOVE LIMIT FACTOR = 3.1250E-02  
 MASS AFTER CONMIN OPTIMIZATION = 1.1575E+01

## STABILIZATION - SIZING CYCLE 4 CONMIN CYCLE 3

CHANGE SET	(VICON) XI	(VIPASA) LAMBDA	(REPET.) ETA	EIGENVALUE NUMBER	THICKNESS FACTOR	MASS AFTER STABILIZATION
0	1.0000	--	0.0000	1	1.000976563E+00	1.1586010E+01

VALUES OF DESIGN VARIABLES:  
 8.619999967E-02 5.251702423E-03 4.028237127E-02 1.199670617E-03 2.695253688E-04  
 1.750274563E-04 3.661751125E-04 3.069789338E-03 1.747000593E-04 7.339396595E-04

MASS AFTER STABILIZATION = 1.1586E+01

FINAL STABLE MASS = 1.1586E+01

## FINAL ANALYSIS

CHANGE SET	(VICON) XI	(VIPASA) LAMBDA	(REPET.) ETA	EIGENVALUE NUMBER	BEST ESTIMATE OF FACTOR	TOTAL AXIAL LOAD	ITEMS TAKEN
0	--	2.5400E-02	0.0000	1	4.471048032E+00	8.5917000E+06	30
0	--	3.8100E-02	0.0000	1	3.484635234E+00	6.6961796E+06	24
0	--	5.7150E-02	0.0000	1	2.776073469E+00	5.3345861E+06	20
0	--	8.5725E-02	0.0000	1	1.970828231E+00	3.7872027E+06	19
0	--	1.2859E-01	0.0000	1	1.394096027E+00	2.6789367E+06	18
0	--	1.9288E-01	0.0000	1	1.136743907E+00	2.1844012E+06	14
0	--	2.5400E-01	0.0000	1	1.113803866E+00	2.1403189E+06	11
0	1.0000	--	0.0000	1	1.000651603E+00	1.9228821E+06	15
0	0.0000	--	0.0000	1	EXCEEDS	1.000651603E+00	
0	0.7500	--	0.0000	1	EXCEEDS	1.000651603E+00	
0	0.5000	--	0.0000	1	EXCEEDS	1.000651603E+00	
0	0.2500	--	0.0000	1	EXCEEDS	1.000651603E+00	

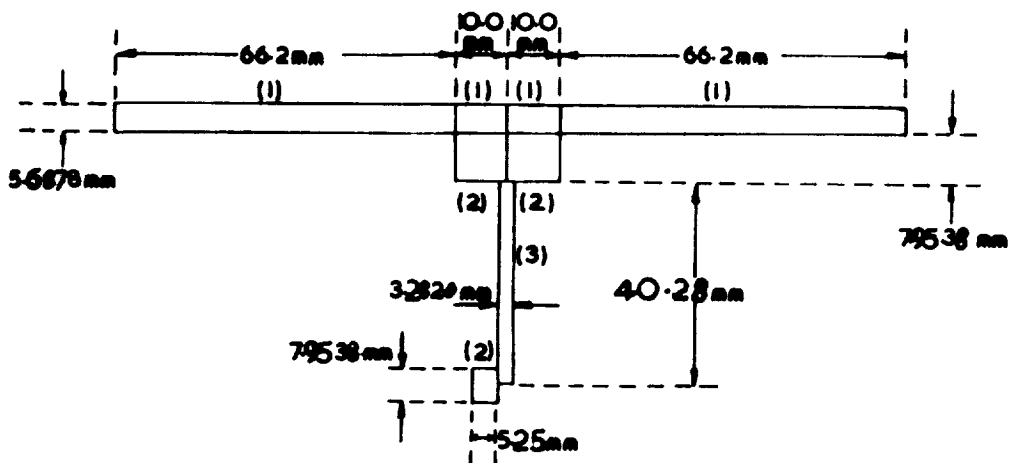
## DESIGN CONVERGENCE SUMMARY

INITIAL MASS = 1.0885E+01  
 INITIAL STABLE MASS = 1.4751E+01

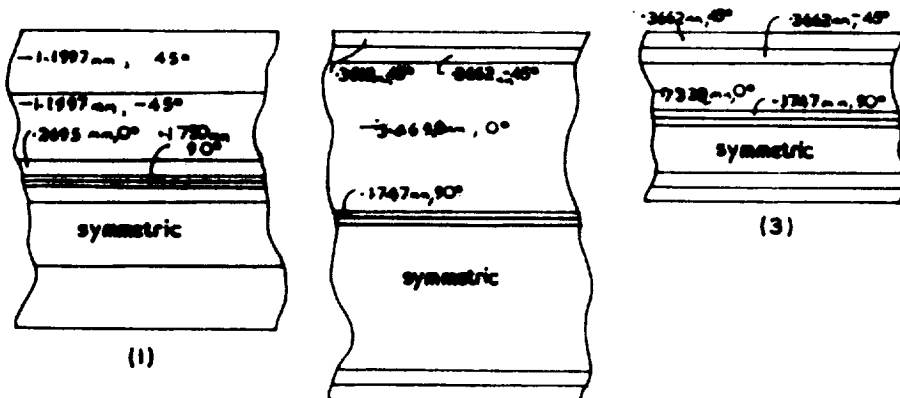
<=SIZING CYCLE=>			<=CONMIN CYCLE=>			CONMIN MASS	STABLE MASS
NUMBER	MOVE LIMIT FACTOR (SMOVE)	MOVE LIMIT FACTOR (FSMOVE)	NUMBER	MOVE LIMIT FACTOR (FSMOVE)	MOVE LIMIT FACTOR (FSMOVE)		
1	4.5000E-01	1	1.0000E+00	8.5926E+00	1.1874E+01		
1	4.5000E-01	2	5.0000E-01	1.1359E+01	1.1936E+01		
1	4.5000E-01	3	7.6134E-01	9.7262E+00	1.1860E+01		
2	4.5000E-01	1	9.0000E-01	1.1242E+01	1.3880E+01		
2	4.5000E-01	2	4.5000E-01	1.1537E+01	1.1600E+01		
2	4.5000E-01	3	2.7100E-01	1.1734E+01	1.1710E+01		
3	4.5000E-01	1	8.1000E-01	1.0890E+01	1.2177E+01		
3	4.5000E-01	2	4.0500E-01	1.1291E+01	1.1778E+01		
3	4.5000E-01	3	1.1957E-01	1.1510E+01	1.1611E+01		
4	4.5000E-01	1	7.2900E-01	1.0975E+01	1.2169E+01		
4	4.5000E-01	2	3.6450E-01	1.1328E+01	1.1750E+01		
4	4.5000E-01	3	3.1250E-02	1.1575E+01	1.1586E+01		

(f)

Figure 6.4 (continued) (f) Selected VICONOPT output: last two CONMIN cycles of the final (fourth) sizing cycle, final analysis and design convergence summary.



(g)



(2)

(h)

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Figure 6.4 (continued) Final design of J-stiffened panel.  
(g) Dimensions of skin and stiffener. (h) Layer thicknesses  
and ply angles, for the three layups identified by (1)-(3) in  
(g).

$$\begin{aligned}
e_{z1}(\text{plate } 7) &= -2t_4 - t_5 - t_6 \\
e_{z2}(\text{plate } 7) - e_{z1}(\text{plate } 7) &= 0 \\
e_{z1}(\text{plate } 8) + e_{z1}(\text{plate } 7) &= 0 \\
e_{z2}(\text{plate } 8) + e_{z1}(\text{plate } 7) &= 0 \\
e_{z2}(\text{plate } 10) &= -2t_1 - t_2 - t_3 - 4t_4 - 2t_5 - 2t_6 \\
e_{y2}(\text{plate } 11) &= 2t_4 + t_6 + t_7 \\
b_5 &= b_1 \\
b_4 &= -b_1 + .0762 \\
b_6 - b_4 &= 0 \\
6t_4 + 3t_5 + 3t_6 + 4t_1 + 2t_3 + b_3 &\leq 0.06
\end{aligned}$$

where  $e_{z1}$ ,  $e_{y2}$  and  $e_{z2}$  denote the values of Offsets in the ALIGNment data (see page 56),  $t_i$  denotes the thickness of layer  $i$  and  $b_j$  denotes the breadth of plate  $j$ . The first six equations define the values of six offsets in terms of plate thicknesses which are design variables, measuring the distance from the plate edges to the nodes marked  $x$  in figure 6.4(b). The next three equations equate  $b_5$  and  $b_6$ , the breadths of the 'reversed' plates to those of the corresponding 'normal' plates and keep the total width of the panel constant. The final inequality imposes an upper bound of 60mm on the total depth of the panel, denoted  $d$  in figure 6.4(b). Note that the nine equations are written with dependent variables on the left-hand side and with design variables and constants on the right-hand side. This is a requirement in the input data for equality linking, but not for inequality linking (see page 82). At any stage in the design process (including the initial analysis), the linking equations are used to assign values to the dependent variables: thus although they have been given their true initial values in figure 6.4(d), any dummy values (or zeros) could have been given in the input data.

As the design is modified, the wavelength parameter ( $\lambda$  or  $\epsilon$ , see pages 12-14) giving the lowest critical buckling load can vary. Therefore it is essential to specify in the Wavelength data (see pages 37-38) an adequate range of values, both for  $\epsilon$  (i.e. using VICON analysis for overall buckling) and for  $\lambda$  (i.e. using VIPASA analysis for short wavelength buckling). In this example, five values in the range  $0 \leq \epsilon \leq 1$  are selected, with the time-saving option  $q = 2$  on the VICON data line which is discussed on page 14, together with a selection of seven values of  $\lambda$  lying between  $\ell/30$  and  $\ell/3$ . (Re-analysis and stabilization, using  $q = 5$ , of the final design

obtained with  $q = 2$ , results in a mass increase of only 0.2 %.

The node numbering used in this example was selected for efficiency, by restricting the nodes in the final structure to those at which POINT supports are attached so as to keep the dominant timing term  $t_5$  (see page 20) as small as possible. This numbering requirement makes the ALIGNMENT data rather cumbersome: key points are that the singly-connected substructure 121 represents a 'J' stiffener, the doubly-connected substructure 12 represents all the skin lying between two adjacent nodes together with the 'J' stiffener at the first of the two nodes, while the singly-connected substructures 122 and 123 represent the end portions of skin, including the line supports on the longitudinal edges of the panel.

The PLOT data has been included in figure 6.4(d) in order to obtain undeformed plots of the panel, together with CROSS-section plots showing details of the layup, for the initial and final designs.

A selection of the output from VICONOPT is given in figures 6.4(e) and (f). The initial configuration is unable to carry the design load, the lowest critical buckling load factors for the VIPASA- and VICON-type analysis being 0.856 (for  $\lambda = \ell/3$ ) and 0.571 (for  $\epsilon = 0.75$ ) respectively, see figure 6.4(e). Therefore, following the initial analysis, the layer thicknesses are all increased by 35.5% (so the panel mass increases from 10.885kg to 14.751kg), achieving a stable configuration from which the first sizing cycle will commence. This sizing cycle includes three CONMIN cycles, two of which are shown in figure 6.4(e), each comprising a call to the optimization routine CONMIN and subsequent stabilization by thickness factoring. Each call to CONMIN uses the sensitivity information which is calculated for the most critical modes (in this case for  $\epsilon = 1.$ , 0.5 and 0.75) at the start of the sizing cycle, but applies different move limits to the design variables. VICONOPT aims to adjust the CONMIN cycle move limit factors so as to minimize the mass after stabilization, but in this case the results from the second and third CONMIN cycles were not as good as that from the first, which was therefore used as the start point for the second sizing cycle. Note that after each design move

the program prints the panel mass and the values of the design variables (three PLate breadths followed by seven LAYer thicknesses).

The printout from the second and third sizing cycles is omitted, but two CONMIN cycles from the fourth (i.e. the final) sizing cycle is shown in figure 6.4(f). The input data specified a minimum of four and a maximum of six sizing cycles (see the DESign line in figure 6.4(d)), and so when the convergence criteria involving CMASS (see page 96) are found to be satisfied after the second CONMIN cycle of the fourth sizing cycle the lowest stable mass found is taken as the final (optimum) design. This design is analyzed in full (using the FAST option), the lowest critical load factors for the VIPASA- and VICON-type analysis being 1.114 (for  $\lambda = \ell/3$ ) and 1.001 (for  $\epsilon = 1.0$ ) respectively: hence it is shown to carry the design load. The design convergence summary in figure 6.4(f) shows that the final design has a mass of 11.586kg, i.e. 6.4% higher than the initial unstable configuration but 21.5% lower than the stable design obtained by applying thickness factoring to the initial design. The dimensions of the final design are shown in figures 6.4(g) and (h), which should be compared with the initial design in figures 6.4(b) and (c) respectively.

## 6.5 Modal Density for Panel on Elastic Foundation

This VIBration example includes some of the less commonly used analysis features of VICONOPT which have not been covered in the previous examples.

The panel illustrated in figure 6.5(a) rests on a Winkler foundation (ref. 14) with out-of-plane stiffness  $k_z = 320 \text{ kNm}^{-3}$  and in-plane stiffness  $k_x = k_y = k^* = 6.4 \text{ kNm}^{-3}$ . Each plate has mass per unit area  $40.23 \text{ kgm}^{-2}$  and stiffness coefficients given by

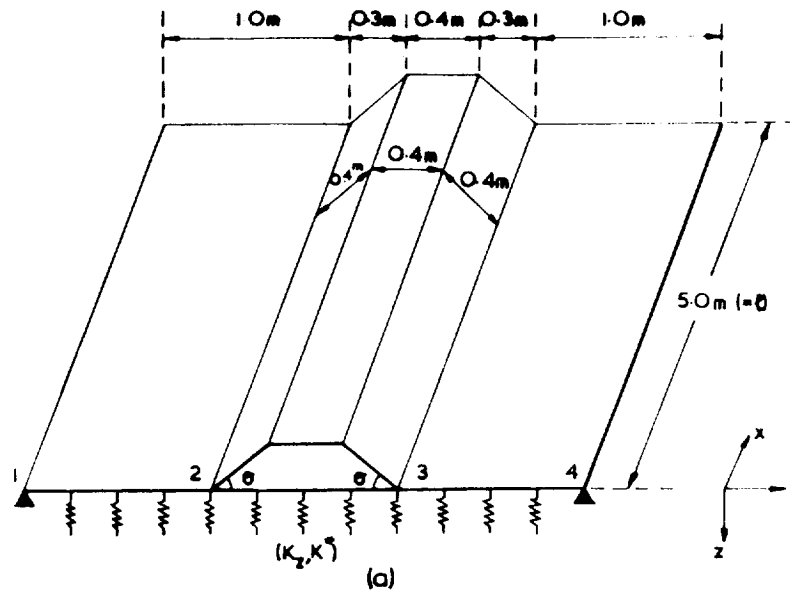
$$[A] = \begin{bmatrix} 16.060 & 6.618 & 0. \\ 6.618 & 15.511 & 0. \\ 0. & 0. & 7.258 \end{bmatrix} \text{ MNm}^{-1}$$

and

$$[D] = \begin{bmatrix} 872.18 & 251.45 & 36.58 \\ 251.45 & 953.45 & 16.12 \\ 36.58 & 16.12 & 284.80 \end{bmatrix} \text{ Nm}.$$

It is required to find the density of natural frequencies in the range 0Hz to 40Hz, for VIPASA-type modes with half-wavelengths  $\lambda = \ell, \ell/2, \ell/3, \dots$ . The input data, listed in figure 6.5(b), specifies that 12 values of  $\lambda$  be included in this series. This is sufficient for this example because the lowest natural frequency exceeds 40Hz for all  $\lambda < \ell/12$ , but VICONOPT prints a warning message whenever the modal density results are misleading because insufficient values of  $\lambda$  have been considered.

The CONnection between nodes 2 and 3 makes use of multi-level doubly connected substructures. In the ALIgnment data (see pages 57-59), the three stiffener portions (plates 3, 2 and 4) are joined to form substructure 5, which is then joined with the skin portion (plate 1) to form substructure 6. Note the negative entry -5 in the definition of substructure 6, indicating that plate 1 and substructure 5 connect the same pair of nodes in substructure 6. The angles of rotation for the inclined stiffener portions (plates 3 and 4) are defined in figure 6.5(c). Each of these plates is derived from plate



```

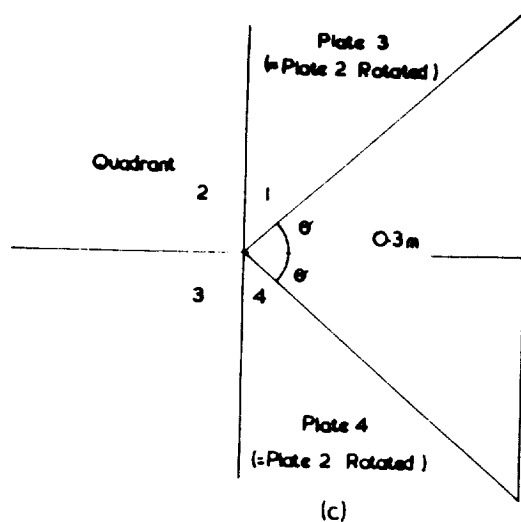
TITLE
EXAMPLE 6.5:  MODAL DENSITY FOR PANEL ON ELASTIC FOUNDATION
VIBRATION
TRIAL VALUES 0. 40.
MODAL DENSITY 10
LENGTH 5.
WAVELENGTH
1 12
WALLS
ANISO 1 40.23  16.060E6  6.618E6  15.511E6  7.258E6 %
          872.18  251.45  953.45  284.80  36.58  16.12
PLATES
1 1.0 1 0 1
2 0.4 1
ALIGNMENT
ROT 3 2 0.
ROT 4 2 0.
5 3 2 4
6 1 -5
CONNECTIONS
1 2 1 2 3 6 3 4 1
ATTACHMENTS
1 901 4 901
LONGITUDINAL LINE SUPPORTS
3
FOUNDATIONS
1 320000. 6400.
ANGLE DEFINITION
3 C V0.3 2 1
4 C V0.3 2 4
END

```

\$ The values of these two angles are defined  
\$ below by the ANGLE definition data

(b)

Figure 6.5 Panel on elastic foundation. (a) Isometric view showing node numbering 1-4, longitudinal line supports (solid triangles) and Winkler foundation stiffnesses. (b) Data input for VICONOPT.

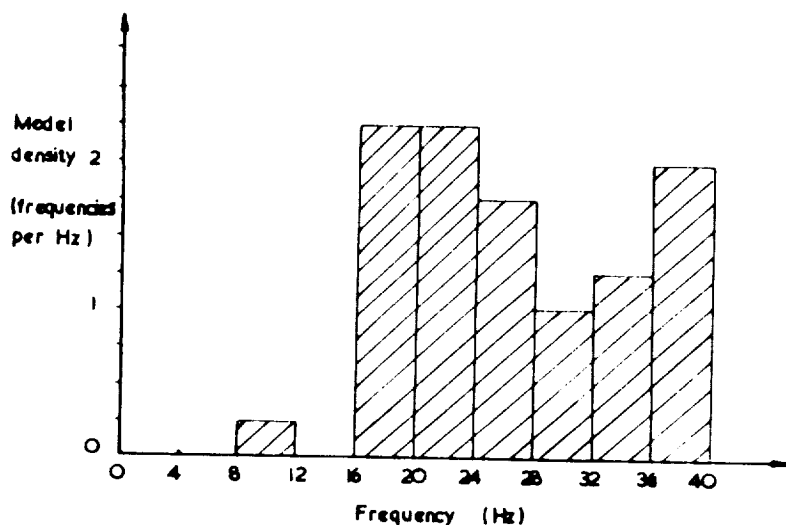


(c)

THE FINAL COLUMN GIVES THE MODAL DENSITIES FOR THE BAND-CENTRE FREQUENCIES OF THE PENULTIMATE COLUMN, AND A BANDWIDTH OF 4.0, ACCUMULATED FOR 12 VALUES OF LAMBDA. (ADDITIONAL INFORMATION ON J-COUNTS IS GIVEN IN THE FIRST FOUR COLUMNS: J IS THE NUMBER OF NATURAL FREQUENCIES WHICH ARE EXCEEDED BY THE FREQUENCY GIVEN TO ITS LEFT.)

LOWER FREQUENCY	J COUNT	UPPER FREQUENCY	J COUNT	BAND-CENTRE FREQUENCY(HZ)	MODAL DENSITY
0.0	0	4.0	0	2.0	0.0000000
4.0	0	8.0	0	6.0	0.0000000
8.0	0	12.0	1	10.0	0.2500000
12.0	1	16.0	1	14.0	0.0000000
16.0	1	20.0	10	18.0	2.2500000
20.0	10	24.0	19	22.0	2.2500000
24.0	19	28.0	26	26.0	1.7500000
28.0	26	32.0	30	30.0	1.0000000
32.0	30	36.0	35	34.0	1.2500000
36.0	35	40.0	43	38.0	2.0000000

(d)



(e)

Figure 6.5 (continued) (c) Definition of angles of rotation for plates 3 and 4:  $\cos \theta = 0.3m / (\text{breadth of plate 2})$ . (d) Modal density results from VICONOPT. (e) Graph of modal density results.

2, which has breadth 0.4m and has a horizontal (y) projection of 0.3m. Thus the angles of rotation are  $\pm\theta$ , where  $\theta = \cos^{-1}(0.3/0.4)$ . Instead of evaluating  $\theta$  in degrees, dummy values have been entered in the ALIGNment data and the angles of rotation have been specified in terms of their cosines in the ANGLE definition data group (see pages 85-87). In each case the absolute value of the cosine is given as the Value 0.3m divided by the breadth of plate 2, with the final integer (1 or 4) specifying in which quadrant the angle lies, see figure 6.5(c). The ANGLE definition group is principally used to specify angles which vary in DESign problems, but may also be used, as in this example, to simplify the data input for fixed angles.

The VICONOPT modal density results are shown in figure 6.5(d). Each line in the table relates to a band of frequencies of width 4Hz. The second and fourth columns (headed 'J count') give the number of natural frequencies exceeded at the lower and upper limits of the band, and the modal density is calculated as the number of frequencies lying in the band divided by its width in Hz. The results are thus presented in a form suitable for plotting, e.g. as in figure 6.5(e).

## 6.6 Calculation of Timing Parameters $\alpha_R$ and $\alpha_C$

The last two examples are included to enable the user to calculate values for the five machine dependent timing parameters defined in section 3.5 (see pages 19-21). The values obtained may then be inserted in the code of the VICONOPT main program (see section A3.1 of Appendix 3, page 165), where they will be used by VICONOPT to estimate the time per iteration for other problems.

Each of the examples uses the CHAnge set facility (see page 104) to define 12 variants of a problem, differing in size and in whether real or complex arithmetic is used. For each variant, six iterations are performed and the CPU time taken for each iteration is printed. The first iteration is a check iteration at trial value zero, for which the time often differs substantially from that for other iterations. The mean time for the other five iterations (i.e. the second to sixth inclusive) should be taken as the time per iteration for each variant of the problem, and plotted against the coefficient of the parameter being sought. (The basic problem, change set 0, should be ignored).

It should be noted that on many computers, particularly those employing time-sharing, solution times may vary considerably if the same problem is run several times. To obtain reliable values for the timing parameters, it is recommended that the iteration times plotted in the following procedure be measured at a time when the load on the computer is light and that they should be checked for accuracy by running the example problems more than once. As an alternative to running the example problems at all, approximate values for the timing parameters may be found by multiplying the values supplied in the VICONOPT main program by a factor derived from manufacturers' information giving the speed of particular computers.

The parameters  $\alpha_R$  and  $\alpha_C$ , which measure the time for Gauss elimination, may be calculated by analyzing the  $m \times n$  grid section shown in figure 6.6(a), for which the data input is given in figure 6.6(c). The CHAnge sets are generated using the values given in the table. Thus for example, change set 42 defines a  $4 \times 6$  grid loaded in shear, as follows:



```

TITLE
EXAMPLE 6.6:  CALCULATION OF TIMING PARAMETERS ALPHA(R) AND ALPHA(C)
ECHO OFF
VIPASA
LENGTH .9525
MATERIALS
1 72.4E9 .32
LAYERS
1 .00213 1
WALLS
1 1
PLATES
1 .1905 1 1
STRESS RESULTANTS
1 0. 0.
ALIGNMENT
ROT 2 1 25.
ROT 3 1 -20.
CONNECTIONS
1 2 1
RESET
NIMAX=-6
$
$ 12 Change sets follow, giving problems of different sizes.
$ By plotting the time per iteration against problem size,
$ the parameters ALPHA(R) and ALPHA(C) may be estimated.
$
$ The data for each change set takes the following form.
$
CHANGE SET (c)
STRESS RESULTANTS
1 {n11} {ns1}
CONNECTIONS
1 2 2
=({1})({1})
=({m})({m})
=({m-1})
=({n})
1 {m+1} 3
=({1})({1})
=({m(n-1)})
$
$ The quantities in {} are to be evaluated from the following table,
$ which also lists the coefficient of ALPHA (R or C) in the timing estimate.
$
$ Change set   Stress resultants   Problem size   ALPHA   Coefficient of
$ number {c}   {n11}   {ns1}   {m}   {n}   R or C   ALPHA (R or C)
$ 11           1.E5       0.       3     2       R       1706.7
$ 12           1.E5       0.       3     6       R       7850.7
$ 13           1.E5       0.       3    10       R      13994.7
$ 21           1.E5       0.       4     2       R       3733.3
$ 22           1.E5       0.       4     6       R      16533.3
$ 23           1.E5       0.       4    10       R      29333.3
$ 31             0.      1.E5       3     2       C       1706.7
$ 32             0.      1.E5       3     6       C       7850.7
$ 33             0.      1.E5       3    10       C      13994.7
$ 41             0.      1.E5       4     2       C       3733.3
$ 42             0.      1.E5       4     6       C      16533.3
$ 43             0.      1.E5       4    10       C      29333.3

```

(c)

Figure 6.6 (continued) (c) Data input for VICONOPT.

```

CHANGE SET 42
STRESS RESULTANTS
1 0. 1.E5
CONNECTIONS
1 2 2
=(1)(1)
=(4)(4)
==(3)
==(6)
1 5 3
=(1)(1)
==(20)

```

The PLates being isotropic, the longitudinally loaded cases (11-13 and 21-23) use real arithmetic and are used to calculate  $\alpha_R$ . The shear loaded cases (31-33 and 41-43) use complex arithmetic and are used to calculate  $\alpha_C$ . The predicted iteration times (see page 21) are  $(\beta_{Rt_1} + \alpha_{Rt_6})$  for real cases and  $(\beta_{Ct_2} + \alpha_{Ct_7})$  for complex cases, where  $\beta_{Rt_1}$  and  $\beta_{Ct_2}$  do not vary with  $m$  or  $n$ . The final column of the table in figure 6.6(c) gives values of  $t_6 = t_7 = 32B^2(N - (2B/3))$ , where  $B = m+1$  and  $N = mn$ . The iteration times for a particular computer are plotted against these values in figure 6.6(b). For example, the iteration times for change set 11 were (.05, .06, .06, .05, .05, .05) seconds, the mean value for the second to sixth iterations being .054 seconds. This value is plotted on the  $\alpha_R$  curve for a coefficient of  $\alpha_R$  equal to 1706.7, see the point labelled {11} in figure 6.6(b). If a straight line is fitted through the six 'real' points thus obtained, its slope is the required value of  $\alpha_R$ . Similarly  $\alpha_C$  is the slope of a straight line fitted through the six 'complex' points.

### 6.7 Calculation of Timing Parameters $\beta_R$ , $\beta_C$ and $\beta_B$

The parameters  $\beta_R$ ,  $\beta_C$  and  $\beta_B$ , which are defined in section 3.5 (see page 19) and measure the time for plate and beam stiffness calculations, may be calculated using a similar procedure to that used to calculate  $\alpha_R$  and  $\alpha_C$  in section 6.6 (see pages 140-143). The first three paragraphs of section 6.6 apply equally to these calculations and are taken as read.

The data input required is given in figure 6.7(a), and defines a dummy structure containing one node at which all freedoms are clamped and having no plate or beam CONnections. However stiffness calculations are performed, in each variant of the problem, for the {np} identical PLates and the {nb} identical BEAMS, as specified in the table. Thus for example, change set 22 defines 60 shear loaded plates and 1 beam, as follows:

CHANGE SET 22

PLATES

1 .01905 1 2

=(1)

==(60)

BEAMS

1 1.E5 385.33 1. 0. 0.01905

=(1)

==(1)

The PLates being isotropic, the longitudinally loaded cases (11-14, for which {nn} = 1) have real stiffnesses and are used to calculate  $\beta_R$ . The shear loaded cases (21-24, for which {nn} = 2) have complex stiffnesses and are used to calculate  $\beta_C$ . The cases with multiple BEAMS (31-34) are used to calculate  $\beta_B$ . A VICON-type analysis is performed with  $\epsilon = 1$  and  $q = 1$ , for which the predicted iteration time (see page 21) is  $(\beta_R t_1 + \beta_C t_2 + \alpha_C t_5 + \beta_B t_8 + \alpha_R t_{10} + \alpha_R t_{12})$ . The terms involving  $\alpha_R$  and  $\alpha_C$  do not vary with {np} or {nb}. For the real plate cases (11-14),  $t_1 = \{np\}$ ,  $t_2 = 0$  and  $t_8 = 1$ . For the complex plate cases (21-24),  $t_1 = 0$ ,  $t_2 = \{np\}$  and  $t_8 = 1$ . For the beam cases (31-34),  $t_1 = 1$ ,  $t_2 = 0$  and  $t_8 = \{nb\}$ . Thus for each set of four cases, the final column of the table in figure 6.7(a) gives the value of the only timing parameter coefficient which varies with problem size.

```

TITLE
EXAMPLE 6.7:  CALCULATION OF TIMING PARAMETERS BETA(R), BETA(C) AND BETA(B)
ECHO OFF
VICON 1 1
LENGTH .09525
MATERIALS
1 72.4E9 .32
LAYERS
1 .00213 1
WALLS
1 1
PLATES
1 .01905 1 1
STRESS RESULTANTS
1 1.E5 0.
2 0. 1.E5
ATTACHMENTS
1 901
LONGITUDINAL
1234
BEAMS
1 1.E5 385.33 1. 0. 0.01905
SUPPORTING STRUCTURES
A 1 901
4
RESET
NIMAX=-6
$
$ 12 CHANGE sets follow, giving problems of different sizes.
$ By plotting the time per iteration against problem size,
$ the parameters BETA(R), BETA(C) and BETA(B) may be calculated.
$
$ The data for each change set takes the following form.
$
CHANGE SET {c}
PLATES
1 .01905 1 {nn}
={1}
==({np})
BEAMS
1 1.E5 385.33 1. 0. 0.01905
={1}
==({nb})
$
$ The quantities in {} are to be evaluated from the following table,
$ which also lists the coefficient of BETA (R, C or B) in the timing estimate.
$
$ Change set      Stress resultants      Problem size      BETA      Coefficient of
$ number {c}      reference {nn}      {np}    {nb}      R, C or B      BETA (R, C or B)
$ 11              1              30       1          R          30.
$ 12              1              60       1          R          60.
$ 13              1              90       1          R          90.
$ 14              1             120       1          R         120.
$ 21              2              30       1          C          30.
$ 22              2              60       1          C          60.
$ 23              2              90       1          C          90.
$ 24              2             120       1          C         120.
$ 31              1              1        30          B          30.
$ 32              1              1        60          B          60.
$ 33              1              1        90          B          90.
$ 34              1              1       120          B         120.

```

(a)

Figure 6.7 Calculation of timing parameters  $\beta_R$ ,  $\beta_C$  and  $\beta_B$ .  
(a) Data input for VICONOPT.

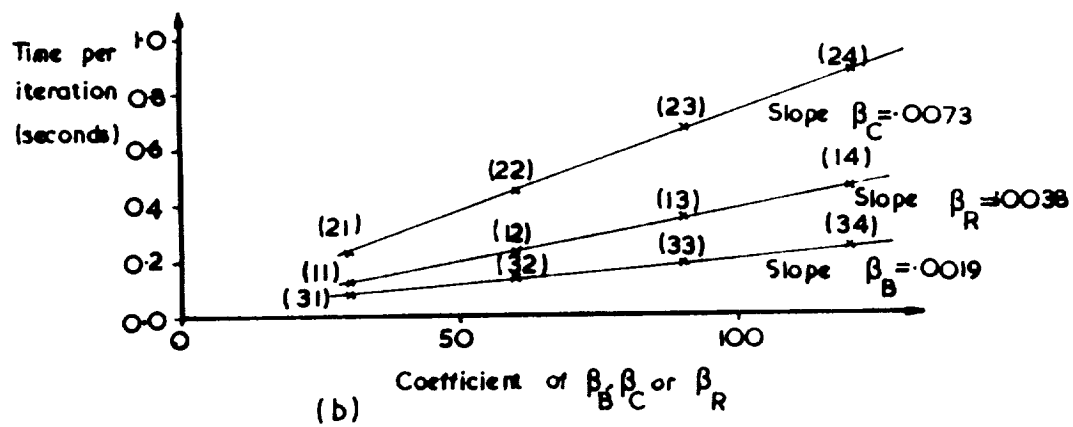


Figure 6.7 (continued) (b) Calculation of timing parameters for a particular computer, each data point being identified by its change set number {c}.

The iteration times for a particular computer are plotted against these values in figure 6.7(b). As in section 6.6. (see page 143), the slope of a straight line fitted through the points in each set gives the required value of the timing parameter  $\beta_R$ ,  $\beta_C$  or  $\beta_B$ .

## 7 ACKNOWLEDGEMENTS

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When preparing VICONOPT and this manual, extensive use was made of the earlier program VICON and its unpublished user manual. Dr C.J. Wright, who was working for British Aerospace at the time (1982) and is now employed by SDRC Engineering Services Limited, made a very large contribution to this earlier work which we acknowledge with gratitude.

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## APPENDIX 1 LOCATION OF REFERENCE SURFACE AND CALCULATION OF [D] MATRIX

The [A], [B] and [D] matrices can be calculated with respect to any reference surface. It is always possible to locate the reference surface such that one  $B_{ij}$  is zero. In VICONOPT the reference surface location is given such that  $B_{11}$  is zero if  $A_{11}$  is larger than  $A_{22}$  or  $B_{22}$  is zero if  $A_{22}$  is larger than  $A_{11}$ . For symmetric laminates this results in all  $B_{ij}$  being zero and to the reference surface being located at the mid-plane of the wall. For an arbitrary layup this is not generally true, so that the theory of VICONOPT which ignores the [B] matrix is not strictly correct and probably would overestimate the buckling loads by an amount depending on the size of the non-zero  $B_{ij}$ .

The [D] matrix can be modified in a way which is believed in most cases to lead to more conservative results. This way is based on the fundamental force-strain relations

$$\begin{bmatrix} [N] \\ [M] \end{bmatrix} = \begin{bmatrix} [A] & [B] \\ [B]^T & [D] \end{bmatrix} \begin{bmatrix} [\epsilon] \\ [\kappa] \end{bmatrix}$$

The largest error from neglecting [B] is likely to be in plates where bending is the most important stiffness in resisting buckling. In this case assume that the items in [N] are set to zero and  $[\epsilon]$  is eliminated to yield

$$[M] = ( [D] - [B]^T[A]^{-1}[B] ) [\kappa]$$

An effective [D] is thus defined as

$$[D]_{\text{eff}} = [D] - [B]^T[A]^{-1}[B]$$

For laminates with a non-zero [B] matrix, the user may choose either [D] or  $[D]_{\text{eff}}$  for all laminates, with the default choice being  $[D]_{\text{eff}}$  (see page 97).

The location of the reference surface of an asymmetric laminate is not generally known beforehand. In the input data, each plate should be positioned so that the mid-surface fits the known line between the two end nodes (with offsets

applied if desired). The program will calculate and print the location of the reference surface. If this does not coincide with the mid-surface, the program will automatically adjust the plate stiffnesses by applying appropriate offsets in the z direction.

## APPENDIX 2 SUBSTRUCTURING AND CYLINDRICAL AXES

This Appendix gives an expanded description, with examples, of some of the features of the ALIGNment data group described in section 5.4 (see pages 53-60). This group applies alignment transformations to plates and substructures, while the analogous BALignment group (see pages 70-73) applies corresponding transformations to beams and beam substructures. References to plates and substructures in the following should be regarded as applying equally to beams and beam substructures.

### A2.1 Description of Substructures

All substructures must be such that their nodes form a chain, in the sense that each node is only connected to the immediately preceding and the immediately following nodes. For purposes of understanding it is essential to imagine these nodes to be numbered  $1, 2, 3, \dots, N_{\text{sub}}$  in sequence along the chain, although these numbers never appear explicitly in the data input. Such substructures can be assembled into further substructures, or into the final structure, in one of two ways. The first possibility is that the only common node between the substructure and the parent structure into which it is being assembled is the node  $N_{\text{sub}}$ . Such substructures are referred to as singly connected. The second possibility is that the first and last nodes, i.e. nodes 1 and  $N_{\text{sub}}$ , of the chain are common to the substructure and the parent structure. In this case the substructure is called doubly connected. It is now possible to be more explicit about the rules governing the assembly of a substructure. Each node can be connected to the two adjacent nodes by any number of doubly connected substructures and/or plates. Also, any number of singly connected substructures and/or longitudinal line supports (defined by the LONGitudinal line supports data input, see page 65) can be connected at any node. In the case of doubly connected substructures nodes 1 and  $N_{\text{sub}}$  will become edges 1 and 2 for the purpose of connection of the substructure to the parent structure. Since other parts of the manual show that the choice of edges 1 and 2 is not arbitrary, it follows that the choice of nodes 1 and  $N_{\text{sub}}$  is uniquely determined, i.e. although there appear to be two

directions in which the user can number the nodes along the chain, only one of them is permissible.

Note that a plate or doubly connected substructure must remain doubly connected, and a singly connected substructure must remain singly connected, whenever a rotation, offset or cylindrical coordinate transformation is applied.

The manner by which substructures are defined in ALIGNment data input enables structures to be specified very concisely, particularly since only one of a set of identical substructures needs to be defined.

## A2.2 Description of Cylindrical Axes

The use of Cylindrical axes (see pages 59-60) may be better understood by examining its relation to the Rotation of a plate. The Rotation data can be thought of as a relative rotation of the yz axes at both ends of a plate or substructure by a clockwise angle  $\mu$ , see figure A2.1(a). If these axes are instead rotated by  $\mu$  at edge 1 and by  $-\mu$  at edge 2, the cylindrical axis system of figure A2.1(b) follows. Plates or substructures are joined by the program in such a way that the yz axes of all plates meeting at a node are common. Hence if two identical plates with cylindrical axes are joined, the second will be rotated from the first by the angle  $2\mu$ , see figure A2.1(c). When cylindrical coordinate transformations are not used, the yz axes remain as an ordinary Cartesian system throughout the structure. Introduction of plates or substructures with cylindrical coordinate transformations causes the yz axis system to be changed for any subsequent node. A plate which is rotated by an angle  $\mu_R$  and then changed to cylindrical coordinates with an angle  $\mu_C$  allows the coordinate system at the edges to be rotated independently by an arbitrary angle  $\mu_1$  on the left and  $\mu_2$  on the right as shown in figure A2.1(d).

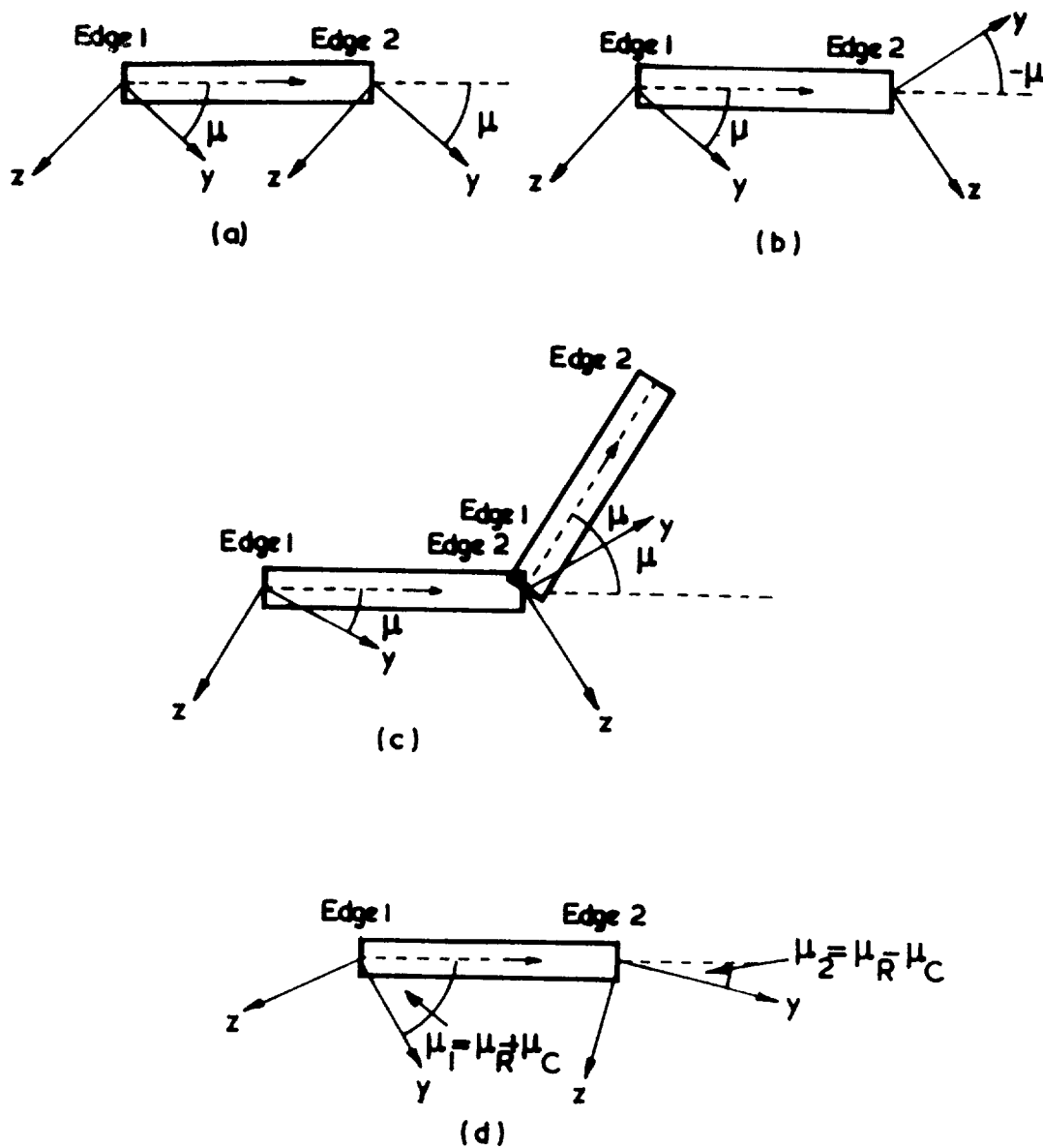


Figure A2.1 Relationship between rotation and cylindrical coordinate transformation. Arrows denote the direction from edge 1 to edge 2 of each plate. (a) Rotation. (b) Cylindrical coordinates. (c) Two identical plates joined in cylindrical coordinates. (d) Arbitrary rotation of axes at both ends of a plate using a combination of rotation and cylindrical coordinates.

### A2.3 Example of Use of Substructures

Figure A2.2(a) shows a stiffened panel. The plates are all anisotropic and those which are identical to each other, including their loading (see  $N_L$ ,  $N_T$  and  $N_S$  on figure 2.1(b)), are denoted by the same letter. Thus there are eight types of plate. It is assumed that PLate data (see page 49) has been used to define plates a - h as plates 1 - 8, respectively. Figure A2.2(b) shows the form of substructuring adopted, which is quite a good one for saving data preparation and computer solution time, although many other ways are possible. Although the cross-section is a complicated one, the six substructures used are quite simple (see figure A2.2(c)) and the ALIGNment data required to define them is very concise, as will be seen at the end of this section.

It will be found that, since  $N_{sub}$  has to be the connection node for singly connected substructures, the preparation of data for substructures 122 and 123 requires the definition of additional plates 9 and 10 in the PLate data, which are inverted versions of plates a and g, in the sense that when rotated by  $180^\circ$  they will become identical, in loading and stiffness, to plates a and g. Thus plates 9 and 10 differ from plates a and g because their shear loadings are in opposite directions and all  $+\theta$  plies are replaced by  $-\theta$  ones (or if Anisotropic WALL data input is being used (see page 47),  $D_{13}$  and  $D_{23}$  have their signs reversed).

The use of substructures 124 and 22 ensures that the nodes of the final structure form a chain, so reducing the bandwidth of the associated stiffness matrix and the solution time, e.g. see the definition of  $t_5$  in section 3.5 (page 20). In a VICON analysis, it is often possible to save solution time by leaving in the final structure only those nodes at which POINT supports and SUPPORTing structures (see pages 66 and 74) are attached.



The data which follows is a complete set of ALIGNment data for the problem, so that it includes Rotation data, Offset data and substructure data, using the rules given for the ALIGNment data group (see pages 53-60). For completeness, the whole structure is then assembled, using the rules given in section 5.5 (see pages 61-63), to give the following ALIGNment, CONNECTION and ATTachment data.

#### ALIGNMENT

```
121 1 901          (assumes line 1 of LON data is the integer 3)
ROT 19 9 180       (rotates plate 9 by 180°)
122 19 901
ROT 20 10 180
123 20
R 18 8 270         (or R 18 8 -90)
124 7 18 123       (not 124 7 123 18)
OFF 24 4 0 2.5 0 2.5 (flanges offset from skin by 2.5)
21 2 -24           (or 21 24 -2)
ROT 15 5 52.5
ROT 25 5 -52.5     (or ROT 25 15 -105)
22 15 6 25         (ALIGNment data ends)
```

#### CONNECTION

```
1 2 21  2 3 3  2 3 22
13 14 21          (triplets need not be in node order)
3 4 21  4 5 1  5 6 1
6 7 21  7 8 22  7 8 3
8 9 21  9 10 1  10 11 1
11 12 21 12 13 3 12 13 22
```

#### ATTACHMENT

```
1 121 5 124 14 122
10 124            (doublets need not be in node order)
```

#### A2.4 Example Using Cylindrical Axes with Substructures

Figure A2.3(a) indicates how cylindrical axes can be used to build up a cross-section which forms part of a regular polygon and which approximates the circular arc shown. The figure shows the y and z axes at the first two nodes. Note that the angle of  $12^\circ$  shown for the left hand plate is negative at edge 1 and positive at edge 2. If the PLate data has been used to define the flat plate as plate 1, the ALIgnment data needed to assemble the cross-section as a substructure, which is then transformed to the global xyz axis system shown, is as follows.

```
CYL 2 1 -12    (puts plate 1 into cylindrical axis system)
3 2 2
4 3 3          (puts the four plates together)
CYL 5 4 48     (transforms from cylindrical to global yz axes)
```

Of course polygonal cross-sections often have many more sides, and would probably need to do so if they are to represent a circular arc type of cross-section adequately. For the cross-section of figure A2.3(b) it is assumed that 12 flats are used to represent the circularly curved portion AB, that 16 flats are used to represent the circularly curved portion CD, that the curved portion EF is identical to AB and that the necessary flat plates have been defined in PLate data as follows. Plate 31 is one of the 16 flats used to represent CD, plate 32 is BC (and DE) and plate 33 is one of the 12 flats used to represent AB.

The ALIgnment data needed to represent the cross-section and transform it to the global yz axis system shown is as follows, where two cases are considered, depending upon whether or not the curved portions AB and EF are included in the cross-section. Note that VICONOPT automatically aligns the plates such that their z axes coincide at common edges. Similarly, if one of the plates is in its natural xyz axis system it is automatically aligned to make its z axis coincide with the z axis of the plate to which it is connected, whereas if the plate has already been rotated as in figure 5.3(b), it and its yz axis system are rotated automatically to make z coincide with the z axis of the plate to which it is connected.

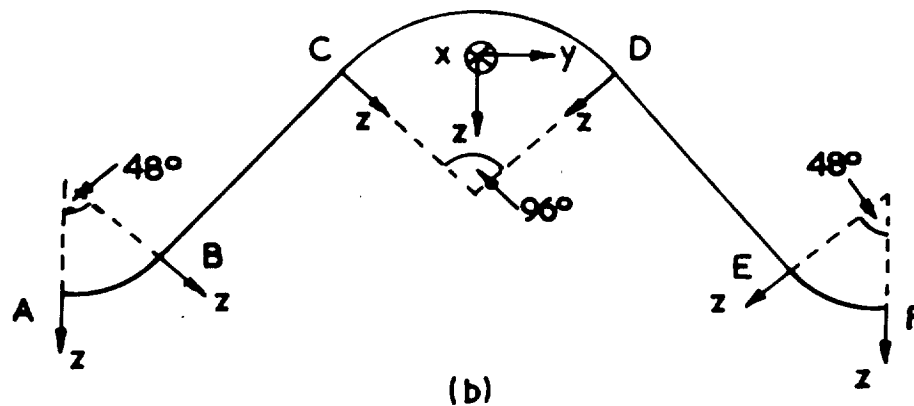
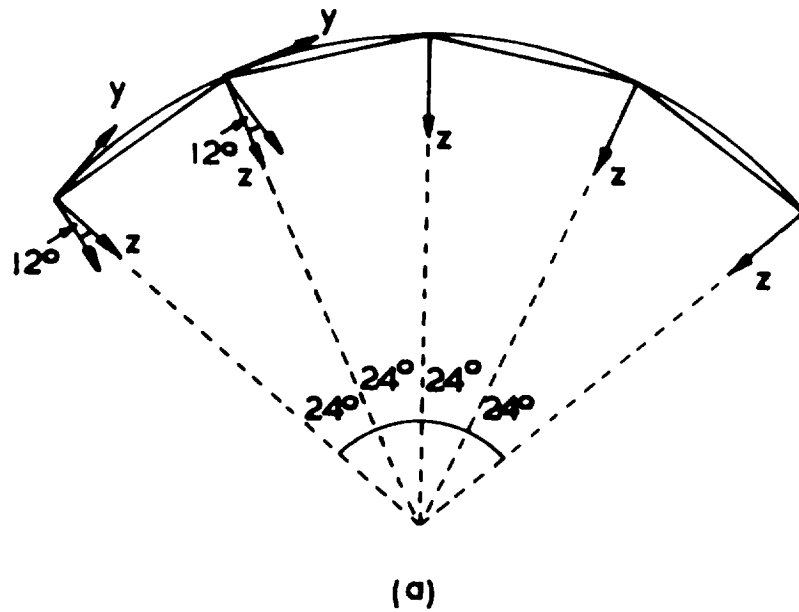


Figure A2.3 Examples showing the use of cylindrical axes with substructures. (a) Cross-section forming part of a regular polygon. (b) Cross-section which involves more advanced use of cylindrical axes. The text shows how closed stiffeners with this form could be included in a modified form of the stiffened panel of figure A2.2 .

The ALIGNment data needed to represent the portion of cross-section BCDE is

```
CYL 41 31 -3
42 41 41      (or, for example,      )
43 42 42      (42 41 41 41 41      )
44 43 43      (45 42 42 42 42      )
45 44 44      (which involves more computation)
46 32 45 32
CYL 22 46 48  (optionally transforms back to global yz axes)
```

whereas the data for the entire cross-section ABCDEF shown is the first five lines above, followed by

```
CYL 46 33 2
47 46 46 46
48 47 47
49 48 48
22 49 32 45 32 49  (transformation from cylindrical to global
                    axes is unnecessary because they coincide)
```

Note that this data can be substituted for that which assembled the substructure 22 of the previous example, so that (for suitably chosen dimensions) the simple type of hat stiffener formed by the three plates e, f and e on figure A2.2(a) is replaced by the more sophisticated closed stiffener ABCDEF of figure A2.3(b).

## A2.5 General Application of Cylindrical Axes

The application of cylindrical axes to many problems is readily apparent and simple. For more complicated configurations there is an approach which is applicable to any situation and which follows a few simple rules. Figure A2.1(d) shows that the yz axis can be rotated with respect to the plate by an arbitrary angle at each edge by using a combination of rotation and cylindrical transformations. It is thus possible, because the desired orientation of all the plates in a plate assembly is known, to define a different direction for the axes at every node. It is doubtful whether such an extreme case would ever be desired, but the method required is of use in defining specific axis directions at particular nodes for practical cases. For example, a restraint might need to be applied in a particular direction which would not otherwise coincide with an axis. The angles  $\mu_i$  in figure A2.1(d) are calculated as

$$\mu_i = \phi - \phi_i$$

where  $\phi$  is the rotation of the plate and  $\phi_i$  is the rotation of the y axis at edge i, with both measured from the same datum direction. Then the required rotation and cylindrical transformation are determined as

$$\mu_R = \frac{\mu_1 + \mu_2}{2} \qquad \mu_C = \frac{\mu_1 - \mu_2}{2}$$

This procedure can be used to define the transformations required to define the geometry of the curved truss-core cylindrical section shown in figure A2.4(a). The configuration is such that each plate forming the skin subtends an angle of  $2\beta$ . The plates forming the triangle 1 2 3 are of equal breadth, so the interior angles are  $60^\circ$ . It is necessary to use the ALIGNment data to give the proper orientation and transformation to only the plates in the representative part of the plate assembly shown in figure A2.4(b). By using cylindrical axes, the plates can be connected without further transformation to form the complete plate assembly. The following table shows for each plate its rotation  $\phi$  and the axis rotation at the edge nodes  $\phi_i$ . Application of the above equations permits the required  $\mu_R$  and  $\mu_C$  of the rotation and cylindrical transformations to be determined.

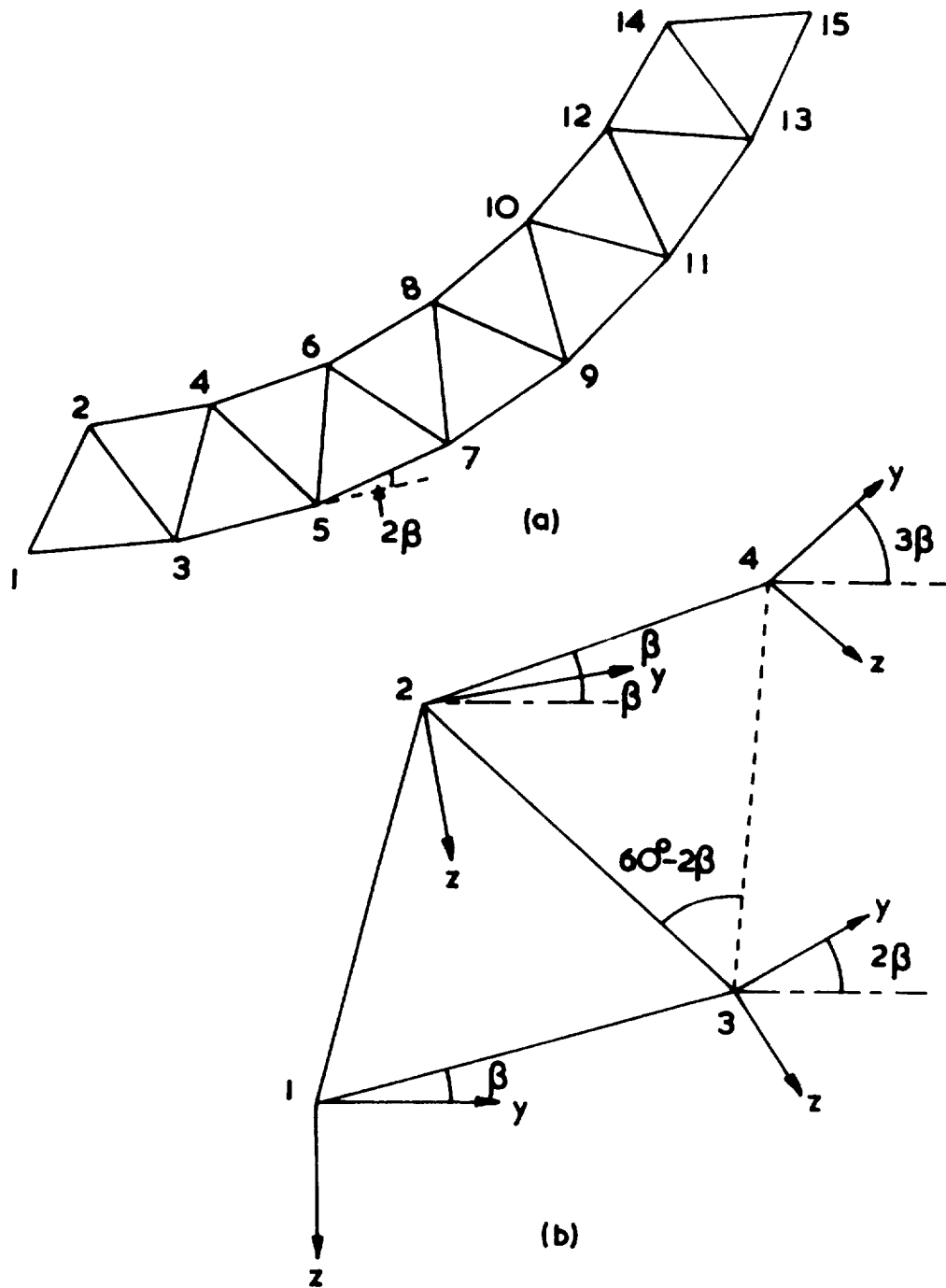


Figure A2.4 Application of cylindrical coordinates to more complex geometries. (a) Curved truss-core sandwich, with nodes numbered 1-15. (b) Geometry of a typical cell, with the value of  $\beta$  exaggerated.

Plate	Plate Rotation $\phi$	Axis Rotation		$\mu_1$	$\mu_2$	$\mu_R$	$\mu_C$
		$\phi_1$	$\phi_2$				
1-2	$60^\circ + \beta$	$0^\circ$	$\beta$	$60^\circ + \beta$	$60^\circ$	$60^\circ + \beta/2$	$\beta/2$
1-3	$\beta$	$0^\circ$	$2\beta$	$\beta$	$-\beta$	$0^\circ$	$\beta$
2-3	$-60^\circ + \beta$	$\beta$	$2\beta$	$-60^\circ$	$-60^\circ - \beta$	$-60^\circ - \beta/2$	$\beta/2$
2-4	$2\beta$	$\beta$	$3\beta$	$\beta$	$-\beta$	$0^\circ$	$\beta$

If the breadth of the plates forming the equilateral triangle is  $b$ , the breadth of the plate connecting nodes 2 and 4 follows from the isosceles triangle 2 3 4 as:

$$2b \sin \frac{(60^\circ - 2\beta)}{2}$$

The PLAtE, ALIgnment, and CONNecTion data to generate this configuration are given as follows for  $b=1.$ ,  $\beta = 5^\circ$  and a plate assembly covering a total arc of  $70^\circ$ :

#### PLATES

1 1. 1

2 .8452365235 1

#### ALIGNMENT

C 3 1 5.

C 4 2 5.

C 5 1 2.5

R 6 5 62.5

R 7 5 -62.5

#### CONNECTION

1 2 6 1 3 3 2 3 7 2 4 4

= (2)(2)(0) (2)(2)(0) (2)(2)(0) (2)(2)(0)

== (6)

13 14 6 13 15 3 14 15 7

The automatic data generation facility is used to repeat the connection 6 times producing an arc of  $60^\circ$  between node 1 and 13. The last 3 connections complete the structure.

### APPENDIX 3 PROGRAM IMPLEMENTATION

Release 1.1 of VICONOPT (in April 1990) comprises about 90 files containing a total of approximately 23000 lines of FORTRAN 77 source code. The program has been developed on DEC VAX computers, but it can be easily implemented on other computers (e.g. IBM, CDC, etc.) by making a few straightforward changes as outlined in this Appendix. In case of difficulties, please contact the third author.

Nine of the supplied files, whose names begin with the characters 'PDP', contain only declarations of named COMMON blocks. These files are referenced by FORTRAN INCLUDE statements in the other source code, but should not themselves be compiled. The INCLUDE statements and filenames are supplied in a syntax appropriate to VAX computers, and may require global changes for other implementations.

The file VICONOPT contains the VICONOPT main program. It contains a number of sizing and initialization statements and is preceded by detailed installation instructions which should be read in conjunction with this Appendix (see section A3.1 below).

The file BDATAVAX is a block data routine which may require modification for non-VAX implementations (see section A3.2 below).

Four of the supplied files, whose names begin with the characters 'PLOT', each contain a set of the four graphics interface routines described in section A3.3 below. Each of the files gives an interface between VICONOPT and a different graphics library. Thus it is necessary to select just one of these files, or to write new versions of the four routines to provide an interface to some other graphics library.

The file TIMER contains a call to a computer-dependent timing routine, and for a non-VAX implementation should be modified as described in section A3.4 below.

The file INIT contains initializations of the default values for RESET variables, which may be altered as indicated in section 5.11 (see page 94).

The remaining files should require no changes for implementation. Most of them contain one FORTRAN subroutine or function with the same name as the file. Exceptionally, five of the files (CONMIN, MELPLT, MODTRN, OUTPT and REED) each contain a collection of logically related subroutines or functions.

### A3.1 VICONOPT Main Program

Before an attempt is made to compile the VICONOPT source code (especially on a non-VAX system), the installation instructions at the top of the main program (in file VICONOPT) should be studied. These incorporate a number of FORTRAN statements which should be altered as required for a particular implementation, as outlined below.

Optional PROGRAM or SUBROUTINE statement at the top of the main program.

IMPLICIT REAL\*8 statement if double precision floating point arithmetic is required. (This is the default setting: any change is required globally in all the source files.)

INCLUDE statements (may require syntax changes globally in all the source files).

Total memory allocation for internal arrays.

Identification of computer and graphics library.

Parameters used for timing estimates (see section 3.5, pages 19-21). Suitable values may be calculated for these parameters by running the example problems given in sections 6.6 and 6.7 (see pages 140-147).

Controls for the banner heading printed at the start of each run, including the VICONOPT version number and release date.

Certain array and common block sizes (should not normally be altered).

Double precision parameter for each particular computer.

Default paper and character sizes for each particular graphics implementation.

FORTTRAN logical unit numbers for the input data file, results file, graphical output file, and for three temporary workfiles.

### A3.2 Block data routine

The file BDATAVAX contains FORTTRAN DATA statements which initialize constant numeric values held in a COMMON block. For the VAX implementation double precision floating point constants are used. For other implementations the numeric values must not be changed, although it may be necessary to convert them to single precision floating point constants.

### A3.3 Graphics Interface Routines

The plotting capabilities of VICONOPT have been designed to be easily portable between computers, so that the amount of implementation-dependent code has been kept to a minimum. This code consists of the four graphics interface routines CALPLT, NFRAME, NOTATE and PSEUDO which may be selected from one of four supplied files whose names begin with 'PLOT'. For example, the versions of these routines given in the file PLOTGINO provide an interface to the GINO graphics library. The file PLOTDUMMY contains dummy versions of the routines which should be used if no graphics capability is required for a particular implementation. Exceptionally, to interface with the LARCGOS system at the NASA-Langley Research Center, these four routines should not be included as part of VICONOPT because routines having the same names and functionality exist as part of the graphics library.

To interface with other graphics systems, new versions of the four routines should be written to the following specifications, using the supplied versions as a guide.

SUBROUTINE CALPLT (X,Y,IPEN) performs different actions depending on the value of the argument IPEN. X and Y are (respectively) horizontal and vertical coordinates, and may be passed in double precision (e.g. for a VAX implementation).

If IPEN = 2, a line is plotted from the current pen position to the point (X,Y).

If IPEN = 3, the current position is moved to the point (X,Y).

If IPEN < 0, the point (X,Y) becomes the new origin of coordinates.

If IPEN = 999, the graphical output file is closed to denote termination of plotting.

SUBROUTINE NFRAME clears the drawing area to denote the start of a new plot.

SUBROUTINE NOTATE (X,Y,HT,BCD,THETA,NOCHAR) outputs on a plot the first NOCHAR characters of the string held in the character variable BCD. X and Y are (respectively) the horizontal and vertical coordinates of the lower left-hand corner of the first character. The characters are drawn with height HT and clockwise orientation THETA degrees from the horizontal. Arguments X, Y, HT and THETA may be passed in double precision (e.g. for a VAX implementation). For calls from VICONOPT, implementation may be restricted to THETA = 0., e.g. see the version of this routine in file PLOTGINO.

SUBROUTINE PSEUDO creates and initializes an output file for graphical pseudo-code. The routine is called with no arguments, and therefore any parameters needed to control the logical unit number used for the file, paper size, etc. must be passed through the VICONOPT COMMON blocks, e.g. see the version of this subroutine in file PLOTGINO.

#### A3.4 Timing Routine

The CPU times printed by VICONOPT are derived from the values returned by a machine dependent routine in file TIMER.

SUBROUTINE TIMER (T) returns in argument T the CPU time (in seconds) since the start of the run. T may be passed as double precision (e.g. for a VAX implementation).

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16. Abstract A computer program which is designed for efficient, accurate buckling and vibration analysis and optimum design of composite panels is described. The capabilities of the program are given along with detailed user instructions. It is written in FORTRAN 77 and is operational on VAX, IBM, and CDC computers and should be readily adapted to others. Several illustrations of the various aspects of the input are given along the example problems illustrating the use and application of the program.					
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